This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 883293

IMMERSE. INTERACT. INVESTIGATE

INFINITY

D2.1 Review of the impacts on cognition, health and well-being for sustained AR/VR headset use

PUBLIC

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PROJECT INFORMATION

Grant Agreement No	883293
Acronym	INFINITY
Name	IMMERSE. INTERACT. INVESTIGATE
Topic	SU-FCT-02-2018-2019-2020
Funding Scheme	Research and Innovation Action
Start Date	01/06/2020
Duration	36 months
Coordinator	Airbus Defence and Space SAS

DELIVERABLE INFORMATION

Work Package	WP2 Analysis of the societal legal ethical and well-being considerations		
Deliverable	D2.1 Review of the impacts on cognition, health and well-being for sustained AR/VR headset use		
Contractual Delivery Date	[M12] 31/05/2021		
Actual Delivery Date	31/05/2021		
Type	R - Report		
Dissemination Level	Public		
Lead Beneficiary	MANZA		
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	Thorsten Stodiek	BHFOD	24/05/2021

REVISION HISTORY

Version	Author Name(s)	Date	Revisions
0.1	Morgane Burgues Alexis Souchet Stéphanie Philippe	09/02/2021	Table of Content
	All partners, Online meeting	18/02/2021	Partners feedback
	Stephanie Philippe, Morgane Burgues	26/02/2021	
	All partners, Online meeting	26/02/2021	Impact of collaboration on the cognitive dimension
0.2	All partners	27/02 – 19/04	Contribution to the document – all sections
0.3	Stéphanie Philippe Morgane Burgues	20/04 – 28/04	Consolidation
0.4	Morgane Burgues Alexis Souchet Stéphane Adamiak Stéphanie Philippe James Fenwick Antonis Karakottas	29/04 – 22/05	Comments and contributions
	Barbara Pirillo Thorsten Stodiek		Review Review

	Graham Kissock James Fenwick Andrea Redhead		Security review Proof read Proof read
	Main partner contributions:		MANZA: 1; 2.1; 2.2; 2.3.3; 2.4; 3.7; 4 CENTRIC: 2.2 CERTH: 2.3.1.1-3 CNRS: 2.3.1.4; 3 DFKI: 2.3.3; 3.1-6
1	Stephanie Philippe Morgane Burgues	26/05/2021	Consolidation of reviewer comments

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D2.1 Review of the impacts on cognition, health, and well-being for sustained AR/VR headset use

EXECUTIVE SUMMARY

This document provides an evaluation of the potential impacts of the use of immersive technologies on the users: potential positive impacts as well as potential negative impacts. We have conducted literature analysis in the different topics and present a report of what has been previously described in various fields, including investigation activities when available. We consider impacts on 3 dimensions: cognition, health, and well-being. For each kind of impact, we investigated means to measure and to mitigate (for negative impact) or to strengthen (for positive impact).

It's important to note that the impacts of immersive technologies on the users, their nature and intensity, closely relate to the technologies that are used. These technologies are rapidely evolving. Considering the current status of the technologies, the main findings can be summarized in three points:

(1) Work in VR on the INFINITY platform should be weighted and dedicated to a limited number of tasks. Even if habituation to VR, which seems to reduce side effects, has been documented, medium to long-term effects is still unknown. The existing literature draws guideline to ensure the user's wellbeing and we must refer to it to develop the platform, to reduce cognitive load and improve motivation and flow at work.

(2) Measuring the effect of several stressors related to tasks in VR should be done on the INFINITY platform. It will help to assess acute stress. Ultimately, it could describe how those stressors can become chronic through episodic exposure, feeding occupational stress. In the short term, those stressors can negatively influence work performances, and INFINITY use-case performances since stress impacts cognitive resources necessary to interact with a virtual environment and conduct investigation-related tasks (data processing, meetings, decision making etc.).

(3) Introducing VR as a new ICT tool requires changes in terms of interaction and interfaces and could impact mental workload. But interaction and the interface themselves could lead to mental overload because they require higher working memory resources. It appears that typical tasks transposed in VR do require more working memory resources, such as reading and writing with a keyboard. However, VR allows information spatialization. Despite requiring higher working memory resources, such spatialization seems to promote high performance when tasks take advantage of spatial information. Typically, data visualization and analytics seem to work well in VR because of these spatial information possibilities.

This document sets the ground for recommendations that will be delivered in D2.2.

ABBREVIATIONS

AI	Artificial Intelligence
ANS	Autonomic Nervous System
AR	Augmented Reality
BCI	Brain Computer Interface
CAVE	Cave Automatic Virtual Environment
CHH	Cartoon Head and Hands
CPU	Central Processing Unit
CSA	Cyber Situational Awareness
CSCW	Computer Supported Collaborative Workspace
CSQ	Cyber Sickness Questionnaire
CWB	Cartoon Whole Body
DOF	Degree Of Freedom
EC	European Commission
ECG	ElectroCardiography
EDA	ElectroDermal Activity
EEG	ElectroEncephalography
EMG	ElectroMyoGraphy
ENS	Enteric Nervous System
fNIRS	functional near-infrared spectroscopy
FOV	Field Of View
GPU	Graphics Processing Unit
GSR	Galvanic Skin Response
GUI	Graphical User Interface
HF	High Frequency
HMD	Head Mounted Display
HMI	Human Machine Interface
ICE	Interactive Collaborative Environments
I^{3}CE	Investigative Immersive and Interactive Collaboration Environment
ICT	Information and Communication Technologies
IR	InfraRed
IVBO	Individual Virtual Body Ownership
LEAs	Law Enforcement Agencies
LF	Low Frequency
LRMB	Layered Referecen Model of the Brain
MoCap	Motion Capture
MR	Mixed Reality
MS	Member Sate
NUI	Natural User Interface
OLED	Organic Light-Emitting Diode
OMG	Open-source Mudra Gloves
OSHA	Occupational Safety and Health Administration
PC	Personal Computer
PNS	Parasympathetic Nervous System
RHH	Realistic Head and Hands
RIA	Research and Innovation Action
RR	Intervals between successive heartbeats
RUB	Realistic Upper Body
RWB	Realistic Whole Body
SA	Situational Awareness

SAM	Sympethatic adrenomedullary
SCL	Tonic Skin Conductance Level
SCR	Skin Conductance Response
sEMG	Surface Electromyography
SMM	Shared Mental Model
SNS	Sympathetic Nervous System
SSQ	Simulator Sickness Questionnaire
STAI	State-Trait Anxiety Inventory
TACIT	Territoriality, Awareness, Control, Interaction and Transitions
TSST	Trier Social Stress Test
VE	Virtual Environment
VIA	Virtual Investigative Assistant
VOG	Video Oculography
VR	Virtual Reality
VRNQ	Virtual Reality Neuroscience Questionnaire
VRSQ	Virtual Reality Symptoms Questionnaire Virtual Reality Sickness Questionnaire
XR	eXtended Reality

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1 INTRODUCTION

1.1 OVERVIEW

Task 2.1 will consider positive and negative aspects impacting AR, VR, and mixed-reality environment users. With older and new generations of apparatus, users have experienced cybersickness, visual fatigue, stress, and mental workload but also increased presence, flow, localization, agency, trust, concentration, and usability. Since these impacts can affect the user's behaviour in immersive reality applications, this deliverable will review current literature based on the proposed applications for INFINITY. In particular, considerations on how they impact (for better or worse) user's behaviour, their ability to understand complex datasets, the way they collaborate, and achieve a proper decision and action plan will be assessed.

1.2 DELIVERABLE POSITIONING

1.2.1 POSITIONING WITHIN THE PROJECT

D2.1 is based on the state of the art and partners experience gained with previous projects; it is developed at the beginning of the INFINITY project before any experimentation.

It is connected to many other tasks in several work packages. It should be considered as part of a consistent approach that will be developed in the project throughout several activities to (1) guide the design of the platform and (2) provide framework and tools for the evaluation of the INFINITY platform's impacts on the users (positive and negative).

At the end of the project, we will compare the platform outcome with the initial state of play and recommendations.

Table 1: Mapping of connections with other activities of the project

Connected activity	Connection description
T2.2	Set the ground for recommendations in T2.2, which may contribute to questionnaires and evaluation framework in WP9
T2.3	In line with the SHIELD framework provided for the development of innovative tools for security and defence activities Specific regulatory framework: use of immersive technologies at work
T3.1	Initiate description of use of immersive environment, with a focus on the user alone, the collaboration dimension will be further investigated in T3.1 and more specific process involved in data analysis and visualisation
T4.1	Specific implementation for LEAs and their workflows (collaboration, data analysis and visualisation)
T7.1	Focus on Data analysis and visualisation in immersive environment, Representation, Manipulation, Interaction, Different kinds of data
T7.6	Monitoring tool kit and associated Equipment
T9.4	Comparison of the results of the experimentation and user's feedback with the initial state of play and recommendations

1.2.2 POSITIONING WITHIN THE IMMERSIVE TECHNOLOGIES

From a technological point of view, we intend to address XR technologies. While it was easy to distinguish AR and VR technologies and devices in the past years, boundaries are now less clear. Devices today allow for a Mixed experience. In the coming years, it will be in the user's hands to define when to switch to a reality-based environment (AR) or a virtuality-based environment (VR) with a given headset. For each topic, we will report the state-of-the-art stemming from AR or VR use but with the objective to build a flexible environment leveraging on the future hardware capacities to offer MR experiences.

1.3 DELIVERABLE STRUCTURE

The first section will introduce the immersive environments and associated technologies. Specifically, the three main components of the immersive environment will be presented, namely, i.e. (i) the hardware and how it contributes to the interaction of the user, (ii) the immersive environment and (iii) the user representation; and how they combine to build the immersive environment and the user experience. This will include a review of the existing regulation regarding the use of immersive technologies at work.

In the second and third sections, the potential positive and negative impact of immersive technologies (see Table 2) and how we can evaluate them, for instance through monitoring physiological parameters and questionnaires, are addressed.

Table 2: Overview of main impacts that will be addressed

Potential positive impacts	Potential negative impacts
Presence	Cybersickness
Flow	Mental overload / Mental workload
Localisation	Visual fatigue
Agency	Muscle fatigue
Trust	Acute stress
Concentration	Techno stress
Usability	
Motivation	

2 IMMERSION: DEFINITION

2.1 IMMERSION: VIRTUAL CONTINUUM

Some researchers have examined the impact of different degrees of immersion on humans. Immersion is defined as being completely involved in the activity of a virtual environment and having the experience or feeling of being present in a mediated environment, different from the present environment (Makransky, Lilleholt, & Aaby, 2017). However, immersion can have a distracting effect on first use (Gay, 1994., Morineau, 2000), but this effect is neutralized if a familiarization phase is offered to learners. This immersion then allows creating an ecological experiment, causing physiological responses which leads to a high potential of performance improvement to retention, representation, or collaboration spots (Knott, 2000, Cresscentini & al, 2015, Joheri 2005, Saleed & Dafoulas,2011, Wasson, 1997, Narayan & al, 2005). Of the various immersive technologies available today, VR would thus be the media bringing a higher degree of immersion, unlike computer or tablet, allowing to be completely involved in the activity of the virtual environment (Muhanna, 2015). Thus, according to the taxonomy of virtual reality systems, with the same virtual environment the degree of immersion is not the same between a VR headset and a tablet: ,, as anindividual's visual system in a simple virtual environment (e.g., tablet or desktop), will only be partially immersed. The immersion will be complete for the individual in a viewing situation with a binocular headset (Muhanna, 2015).

As suggested above, while talking about immersion, it is essential toessential to distinguish between the **content** and the **device** used to display the content. Furthemore, the system may also include various ways to capture user behavior, relying on input into the system and providing feedback to the user. To summarise, it can be reported the definition of Virtual Reality proposed by Sherman and Craig (2003): (1) a virtual medium (2) bringing an immersive state, (3) sensory feedbacks (4) and interactivity.

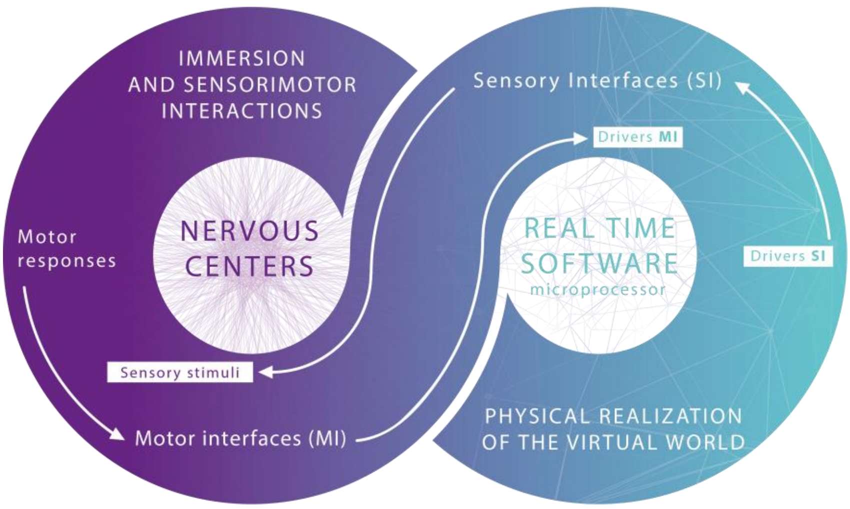


Figure 1: Technocentric diagram of Immersion and Interaction based on Fuchs *et al.*, 2006, p. 11

Regarding the content, one can refer to the theory of the Virtuality continuum, described hereafter.

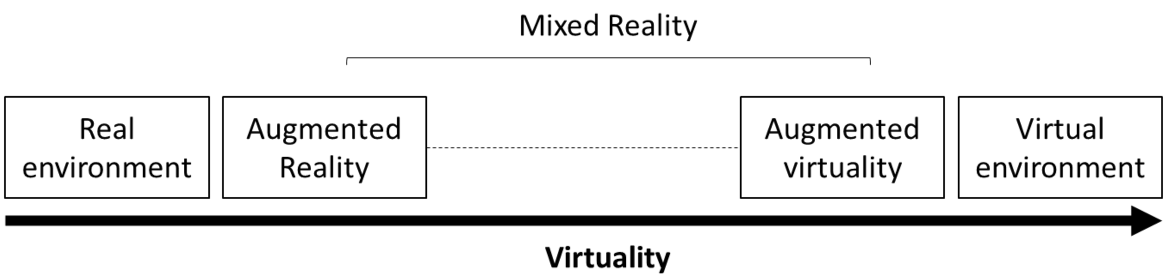


Figure 2: Virtuality continuum, described by (Milgram & Kishino, 1994). The continuum includes Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), altogether identified as eXtended Reality (XR).

This continuum describes the different levels of virtuality existing (AR, MR, VR), that are all components of the eXtended Reality (XR), starting from real environment to virtual environment (entirely 3D environment without any real data input), with several mixtures thereof in between, including:

- **augmented reality**, defined as the semantic and spatial association of real and virtual computer-produced objects (Anastassova, 2007; Caudell and Mizell, 1992),
- **augmented virtuality**, corresponding to the addition of photo, video, or other real media in a virtual environment (Milgram and Kishino, 1994).

Regarding the device, it is usually agreed that specific devices are used for these different kinds of content, with a major difference between AR devices and VR devices:

- Augmented reality devices allow the user to see the real world immediately surrounding and add synthetic content in this real world. Examples of AR devices are Microsoft Hololens headsets (Microsoft, s.d.) and mobile phones.
- Virtual Reality devices isolate the user from the real world and display a synthetic environment to immerse the user. Examples of VR devices are CAVE (Wikipedia, s.d.) and HTC Vive (Vive, s.d.)

However, the technologies and devices are rapidly evolving, and the trend is for these technologies to convergence and extend the possibilities. For instance, cameras on the HMD can be used to allow the user to see the surrounding environment as if the device is transparent. It can be anticipated that the future generations will offer the possibility for the user to define the degree of real versus virtual content, depending on the experience required.

The technologies and devices are more extensively described in **D3.1: Research report on immersive reality, collaborative, and analysis methods**. The following sections focus on the interaction and sensory feedback, and develop the user's perspective, his/her interaction with the system, and the potential impacts of the system on the user.

2.2 CHARACTERISTICS OF IMMERSIVE ENVIRONMENTS AND POTENTIAL IMPACT ON USERS

Virtual Reality has been defined as a scientific and technical field that uses information technology and behavioural interfaces to simulate in a virtual world the behaviour of 3D entities, which interact in real-time with each other and with one or more users in pseudo-natural immersion via sensor-motoric channels (Fuchs et al., 2006). As such, VR is based on two concepts: immersion and interaction (technological dimension) and contributes to presence (psychological dimension), i.e., “the strong illusion of being in a place in spite of the sure knowledge that you are not there” (Slater et al., 2009). Presence has been further defined by 3 major components, which provide indications of factors contributing to a high-quality experience (Lee, 2004):

- *Physical presence*: "the extent to which one feels present in the mediated environment, rather than in the immediate physical environment" (Biocca, 1997; see p. 30). This is supported by the perception of objects in the virtual environment as real objects, the possibility of locating one's body in relation to the environment or carrying out spatialized actions.
- *Self-presence*: "a psychological state in which virtual (para-authentic or artificial) self/selves are experienced as the actual self in either sensory or non-sensory ways" (Biocca, 1997; see p. 46). It relates to how connected one feels to his or her virtual body, emotions, or identity.
- *Social presence or co-presence* is understood as "the sense of being together with another and mental models of other intelligences" (Biocca, 1997; see p. 42). It depends on the ease with which one perceives to have "access to the intelligence, intentions, and sensory impressions of another" (Biocca, 1997).

Augmented Reality offers similar opportunities to interact with virtual representations of information, objects and participants that are not physically present around the users. The idea of presence is therefore only partially supported.

Virtual Reality and Augmented Reality, depending on the environment provided, the interactions, and the participants can simulate different experiences and provide new ways to engage with digital content. Thereby, eXtended Realities allow users to experience, try, create, and act, rather than sole observation (Mikropoulos & Natsis, 2011; Slater & Sanchez-Vives, 2016). Interactions are possible with the environment and objects and other participants, possibly remotely, or with agents, offering new opportunities to collaborate (Zheng et al., 2018). Depending on the identity of other participants or of the avatar the user is embodying, VR can induce modifications of behaviour, adopting attitudes of their avatar's (Ratan et al., 2020) and enhance Empathy-Related Abilities (Bertrand et al., 2018). In addition, VR and AR provide unique 3D representation possibilities to create 3D models and make concepts tangible (Dede et al., 1996) and to represent what is barely accessible (Freina & Ott, 2015) or hardly available such as complex data sets Olshannikova et al., 2015).

Key user-experience factors include usability, learnability, guessability, sense of comfort, physical effort to utilize the device's capability, and trust (De Paolis, L. T., 2020). **Usability** is mainly impacted by the ease of navigation inside the virtual environment (VE) and the ability to perform selection and manipulation tasks inside it. On the other hand, the sense of **presence** is mainly affected by the ease of interaction (i.e., usability) within the VE (Stanney, Mollaghasemi, Reeves, Breaux, & Greaber, 2003). In other words, users can better experience the sense of presence when they are not distracted by difficulties in interacting with the environment. **Guessability** refers to the ability of the user to guess on how to utilize the device capabilities to accomplish the desired task, without a formal, explicit learning phase. In contrast, **Trust** refers to the belief of the user that his intentions will be accurately reflected in the VE through the capability offered by the utilized device.

The range of opportunities offered by immersive experiences strongly depends on the **hardware** used and **stimulated senses**. It is hereafter presented a (non-exhaustive) overview of the existing technologies. The purpose of this document and the following sections, is to evaluate how these may impact on the user.

Burkhardt has described four types of interaction devices used in VR (Burkhardt, 2007):

- position and movement capture devices
- visual presentation devices
- proprioceptive and skin feedback devices
- sound input and presentation devices.

This first list has been further enriched with gesture interaction devices (Li, Huang, et al., 2018):

- Touch device (touch screen, stylus pen)

- Computer-based vision interaction (camera, infrared camera) allowing monitoring and evaluation of behaviour in the immersive environment.

Other modes of interaction can also be mentioned:

- Voice command: relying on speech recognition technologies, voice command is part of emerging approaches that one can think of implementing in VR. The number of consumer devices with built-in capabilities for Automatic Speech Recognition (e.g. personal assistant) is increasing with the improvement of technology reliability. Voice commands associated with a speech synthesis feature could be part of a natural interaction system for immersive environments (see section 0 page - 31 -).
- Brain Computer Interface (BCI): the underlying principle is to collect brain activity signals through EEG and to translate them into instructions for the digital system (see Arico et al., 2020 for recent overview). Long restricted to laboratory applications, BCI could come to the consumer market in various fields thanks to advances in sensors to collect data and algorithms to treat the collected data. One of the primary applications is to replace or restore interaction capacities of locked in people (e.g. amyotrophic lateral sclerosis patients). But other potential applications can be found in immersive environments. In a recent review, Putze et al., 2020 explored the scope arising from the convergence of BCI and AR/VR fields of research. They highlight that immersive technologies are anan opportunity for the development of BCI (e.g. for rapid prototyping of new interface paradigm and evaluation). Conversely, BCI is an opportunity for the development of new interaction modes in immersive environments. Among other applications is the development of rehabilitation programs based on the control of an avatar using BCI.
- Olfaction: olfactory sense can be used to further stimulate the user with the objective of reinforcing the realism of the experience. Few consumer headsets are available on the market but the use remains anecdotal and out of the scope of the INFINITY project.

In the scope of this document, the focus is on the most relevant technologies regarding the INFINITY project, in terms of robustness and easiness to deploy.

2.3 XR INTERACTION DEVICES, IMMERSIVE ENVIRONMENT AND USERS

We describe in the following section 2.3 four main topics:

- The hardware (display, interaction, feedback)
- The immersive environment
- The representation of users in the environment
- A fourth subsection proposes a general interaction framework, based on Natural User interface and involving different modes (paradigms and technologies).

How these components of the virtual environment are connected and the associated impact on the users will be addressed in section 3.

2.3.1 HARDWARE

While a detailed description of the internal technology of XR interaction devices is given in D3.1, here we will focus on describing the capabilities enabled by those devices from the perspective of user experience. Some capabilities can only be offered by specific devices (e.g., haptic feedback can be better experienced by haptic-enabled gloves). But others (e.g., hand tracking) can be offered by a broader range of devices (e.g., infrared/colour/depth sensors). Also, more recent technologies like eye tracking, now available in consumer device and brain-machine interface, are considered

2.3.1.1 HEAD-MOUNTED DISPLAYS

The most critical user experience factors to consider when evaluating the overall performance of the different XR interaction devices can be divided into two separate groups. The first group contains unique and related factors to the device itself. The second group includes factors related to the device's functional capabilities, regardless of the type of the device itself. Key user experience factors include usability, learnability, guessability, sense of comfort, physical effort to utilize the device's capability, and trust (De Paolis, L. T., 2020).

Figure 3: VR Headsets (©Oculus / © HTC VIVE / © Vale Index)

Three types of HMDs are available for the general public: depending on smartphones, standalone (some models can also be interfaced with a PC), and depending on a PC (Fuchs, 2017). Each also depends on components: screen, lenses, CPU/GPU, sensors, and headphones.

Screens: the two most widely used display technologies in current headsets (Anthes et al., 2016) are LCD (Liquid Crystal Display) (Mosley, 1993) and OLED (Organic Light-Emitting Diode) (Tyan, 2011). According to Chen et al. (2018) the competition between the two display technologies will continue over time as the comparative performances are balanced according to the use, especially for VR. According to Kim et al. (2017), when comparing LCD and OLED on several parameters (black depth, resolution, power consumption ratio, ability to bend the screen, blurring when moving in the image), OLED seems to be the most appropriate for making an HMD. New technologies are also being developed. Regardless of the screen, these HMD characteristics must satisfy the human visual system. This is not currently the case, however, screen technologies evolve every year (Jang et al., 2019).

Lenses: the screens of the video headsets are very close to the human visual system and lenses are necessary to shift the image (position of the focal plane) and allow its perception. Chromatic aberration is one of the effects of VR head mounted display use (Beams et al., 2019). Some lens technologies are aimed to improve these accommodation issues in HMDs (Y.-H. Lee et al., 2017). The combination of displays (their size) and lenses (their physical properties) affect the size of the field of view (FOV), which is currently below human capabilities in most HMDs (Fuchs, 2017).

Processing units: the computational function of the headset displays is operated by the graphics processor unit (GPU) (Brodtkorb et al., 2013). The image refresh rate, the speed of restitution of the image changes, and stereoscopic images are dependent on this component of the HMDs or smartphones (Capin et al., 2008). The central processing unit (CPU) orders, manages, and distributes the instructions of the (calculation) programs. This distribution of computation and computational power is essentially confined to the devices (HMDs), but remote solutions (cloud) are being tested (Kämäräinen et al., 2018).

Sensors: maintaining coherence between the body's movements, the head, and the images projected by the HMD involves sensors (Gourlay & Held, 2017). The techniques employed vary according to the type of HMDs. HMDs with smartphones depend on a: Magnetometer, Accelerometer, and Gyroscope. PC-based HMDs implement some of the same tracking elements but often depend on external trackers: mainly infrared (Niehorster et al., 2017). Stand-alone HMDs have been developed with inside-out tracking technology: the trackers are directly integrated into the HMD. Dependent HMDs rely more and more on this tracking strategy as well. Depending on the technologies that are implemented, it is possible to distinguish two categories of HMD with different degrees of freedom (DOF): first generations HMD only provided 3 DOF, while more advanced devices and latest generations offer 6 DOF, i.e. the possibility to track user movement in the environment, not only the orientation. For more detail about these aspects, please refer to D3.1.

Headphones: visualization might be the first purpose served by the **VR headset**, however, audio is a crucial component of immersion (Hacihabiboglu et al., 2017). Headphones are increasingly integrated directly into HMDs. Sound tends to be spatialized in HMDs (Cooperstock, 2011; C. H. Lee, 2017).

Tracking head movements to interact: by utilizing HMDs, the users viewpoint inside the VE adjusts based on inertial and gyroscope sensors. This change in viewpoint can also infer user's gaze orientation (i.e. *head orientation*, see section 2.3.1.4 page - 24 - for accurate gaze tracking using eye tracking with internal HMD sensors), eventually implementing an implicit method to realize **gaze tracking**. This interaction mode can also be implemented with AR devices. Through gaze tracking, the user can interact with the VE by pointing to specific directions of the virtual world, possibly performing actions like selection in a menu and zoom in/out to specific portions of the screen. The choice confirmation can be achieved with a keyboard, a controller, or head-fixation for a predefined amount of time. Headset orientation tracking is pretty accurate since the first generation of VR headsets and inspires guess ability and trust with a low learning curve. However, depending on the application, frequent, large head orientation changes may introduce user discomfort and fatigue. This interaction mode is also very limited. Other technologies and approaches have been developed to enrich interaction modes that will be described in the following sections.

2.3.1.2 HAND INTERACTION DEVICES

This section describes various technologies that enable hand motion tracking through the use of devices external to the HMD itself.

2.3.1.2.1 TRACKING HANDS WITH CONTROLLERS

Apart from the HMD itself (via head movement tracking above described), the first way for end-users to interact with virtual environments has been through **controllers**, most often bundled with the VR headsets themselves, as well as with some AR headsets. Different vendors provide different ergonomic designs for the controllers. However, from a macro-perspective, those controllers offer orientation tracking through **inertial and gyroscope sensors (3 DOF controllers)** and, additionally, in some setups, also **positional tracking (6 DOF controllers)**. Further, controllers can come with a D-pad (HTC VIVE) or joysticks (Oculus Touch) in addition to traditional buttons. Most VR controllers also offer haptic feedback through vibration. Applications utilize VR controllers to allow users to interact with the VE, either with a point and click rationale or via controller motion analysis, translating gestures of controller motion and button clicks to actions inside the VE.

Figure 4: VR Controllers (Oculus Touch 1st Gen / Oculus Touch 2nd Gen / HTC Vive / Valve Index)

VR controller technology is arguably one of the most mature, stable, and accurate technology for XR interactions. Most users would feel natural to use VR controllers inside a VE in a similar way as they would use joysticks or gamepads found in video game consoles and PC games. Thus, part of the ease of use of VR controllers is due to the well-established position of game controllers in the video game entertainment industry since the early '80s, which led to an increased familiarity of end-users with this type of device. In that sense, VR controllers are rated high in terms of learnability. In numerous scientific studies, the stability and accuracy of VR controller position and orientation tracking is so mature that VR controllers are one of the most trusted XR interaction systems by end-users. (i.e., users are confident that their intentions are mapped to actions in the VE as expected). This however does not rely on actual functional evaluation of task performance, and previous studies have demonstrated that preventing the user from getting use to an interface does not need to be considered while designing a Human Machine Interface (HMI) (Wigdor D. & Wixon D., 2011). Depending on how the application uses the VR controllers, the guessability factor of VR controllers may often be increased. VR controllers can be tracked anywhere inside the physical user-area and independent from the user's head orientation - enabling complex VR interactions. However, controllers have a drawback because users need to constantly hold them in their hands, irrespective of their intentions to interact with the environment. This has a slight negative impact on user comfort compared to other modalities, which is, however, mitigated by the increased trust that users have in them. Additionally, the, albeit basic, vibration haptic feedback they can provide positions them in a favourable position compared to other XR interaction modalities, which do not offer haptic feedback at all (i.e., interaction via pure hand gestures). Lastly, one specific type of VR controller, namely the Valve Index, utilizes an additional array of sensors on the controller to track hand/finger position, motion, and pressure allowing for fine-grained interaction with the VE, compared to other typical VR controllers. (Fahmi, F., 2020; Gusai, E., 2017; De Paolis, L. T., 2020; Caggianese, G., 2019).

2.3.1.2.2 TRACKING HANDS WITH CAMERA AND SENSORS

More recently, since Q2 2020, the most modern way for end-users to interact with VR environments is through **hand tracking/hand gesture recognition** offered by inside-out **cameras** attached to VR headsets themselves. This holds for the latest most popular headsets like Oculus Quest 2 and HTC VIVE Pro / Cosmos. Hand tracking and hand gesture recognition, in general, can be supported by vision-based external sensors (i.e., depth / infra-red / colour / mono-chromatic external cameras). The integration of such sensors in the latest VR headsets facilitates, apart from inside-out tracking of the headset's position and orientation, the recognition and tracking of user's hands, easing accessibility to the new hand tracking/hand gesture recognition modality.

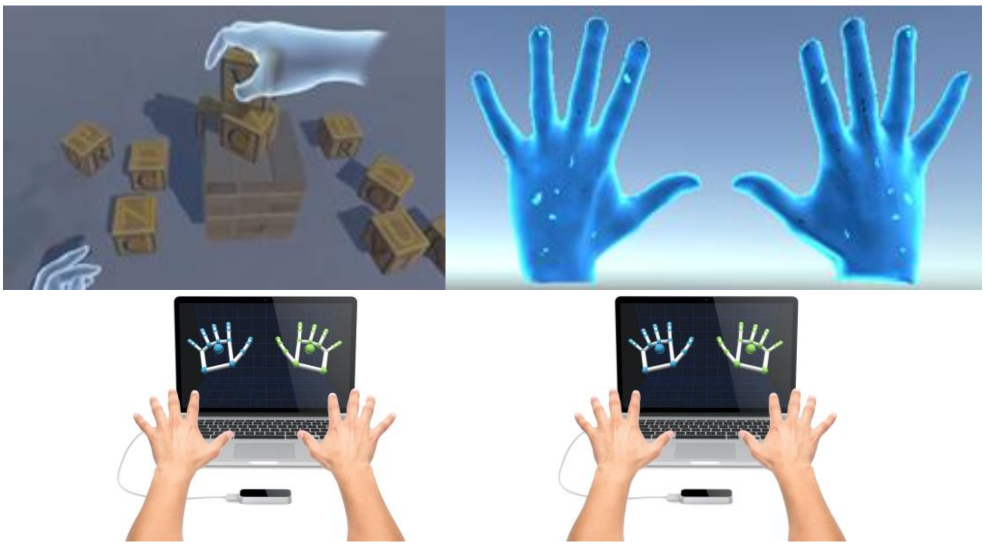


Figure 5: Hand tracking (Oculus / Vive), Leap-Motion

Different headsets have different capabilities regarding hand tracking, with most powerful headsets offering full skeletal tracking of all finger joints. In contrast, less powerful models (in terms of processing power) are only limited to offer recognition of specific hand gestures and not a full skeletal model of the user's hands.

The integration of hand tracking to VR headsets is very recent and prior works on hand tracking in VR environments utilized the external (to the headset) stereo infra-red (IR) sensor **Leap Motion**. The new integrated technology in VR headsets brings portability and easy access to the hand-tracking technology compared to the previous solutions based on the Leap Motion sensor, with on-par or even better performance accuracy.

Current literature lacks systematic evaluations of the latest hand tracking technology found in VR headsets. However, many studies exist based on hand tracking offered by the Leap Motion sensor comparing user experience between hand tracking and other modalities such as VR controllers and Gloves (see for instance Cortez-Perez et al., 2021). One of the most important key findings in the literature is that due to hand-tracking technology being less accessible than VR controllers, end-users are significantly less familiar with utilizing their hands in mid-air to interact with VEs. This may be explained by the fact that, hand tracking technology is less mature technology and has been, until recently, less robust and accurate than the technology behind VR controllers. Users often spend a significant amount of time correcting their - not correctly recognised - actions, instead of focusing on the VR experience, hampering their sense of presence. In recent studies, end-users require more trials and significantly more time to accomplish object manipulation tasks in VEs with hand-tracking than by VR controllers.

Other limitations have been pointed out, so hand tracking should be considered with care. For instance, specific gestures may require more muscle groups than others, possibly being less comfortable for the end-users (Caggianese, 2019), see section 3.2.3. Further, this modality does not provide any haptic feedback compared to other alternatives. (Gusai, E., 2017; Fahmi, F., 2020; Voigt-Antons, 2020).

Arguably, if stable and accurate, hand-tracking can be an enabler for many interesting VR interactions due to its ability to bring metaphors from natural interactions to the virtual world. The design of hand gestures for various contexts is an active literature area. Soon, with the new era of hand-tracking technology brought by VR headsets, significant progress are expected in the field of hand gesture design. Overall, hand tracking is an enabler for hand gesture recognition and more natural interaction with VEs. Caggianese (2019*)* stresses that gestures in virtual environments need to mimic the real-world interaction to feel intuitive (e.g, grabbing using thumb and index fingers feels more intuitive than making a fist gesture). Learnability, guessability, comfort, and physical effort considerations of hand gestures enabled by hand-tracking is left to the application's developers to decide. Depending on the virtual environment context, different gestures may feel more intuitive than others. This field can be connected to the notion of Natural User Interface (NUI) and multimodality, that will be developed in the section 0

Natural user interface and multimodality page - 31 -.

2.3.1.2.3 TRACKING HANDS WITH GLOVES

Achieving similar to, or even better, hand-tracking accuracy vision-based hand-tracking with **motion capture gloves** is possible (e.g., Manus, Hi5). Gloves have the advantage over vision-based HMD hand-tracking, to track hand pose even when hands are out of the headset cameras' sight. However, most of the gloves available on the market suffer from the major drawback that no one-size fits all hands. Gloves of different sizes are required for different people, and usually quite expensive. Most gloves offer sufficient degrees of freedom to track all fingers accurately. However, some open-source designs (e.g., Open-Source Mudra Gloves – OMG) are specifically designed to be low-cost (Freire et al., 2020). They fit a broader range of hand sizes and are targeted to detect specific pinch gestures performed with the thumb and the index or the middle fingers. In this open-source design, it is impossible to track finger pose but only recognize the pinch gestures themselves. Most characteristics are shared with the pure vision–based hand tracking of VR headsets regarding glove user experience. Users tend to not prefer gloves in favour of VR controllers or vision-based hand-tracking (Fahmi F. 2020). But the users also found their experience with gloves more suitable to complete their task in VR (Glowacki D. R, 2020). Gloves are an enabler for hand gesture recognition. Part of their user experience depends on how the application maps the recognised gestures to actions inside the VE. Even though gloves may offer more robust hand tracking than pure vision-based algorithms, gloves are not necessarily preferred than vision-based, non-wearable hand tracking (Fahmi F., 2020).

Figure 6: Motion capture Gloves: left, Manus-Hi5; right Prime II © Manus™

Apart from typical motion capture gloves, which allow for accurate finger tracking, **haptic gloves** enable tactile and kinaesthetic feedback to the end-user to enrich the sensation of object texture and resistance (Perret, J., 2018). Haptic gloves often are heavier than lightweight motion capture gloves. This is due to the need for them to have vibrotactile actuators or exoskeletons to provide vibration and force feedback to the end-users. Among all the previously mentioned interaction devices, haptic gloves convey the more accurate user experience in terms of haptic feedback. They allow to go beyond basic vibration enabled by VR controllers. Haptic gloves also provide higher feedback than vision-based hand tracking.

2.3.1.2.4 ELECTROMYOGRAPHY

In addition to the previously mentioned approaches, another way to interact with VR is via hand gesture recognition through **surface electromyography (sEMG) sensors** usually placed either in the forearm or at the wrist (e.g., Myo armband by Thalmic Labs or Kai Gesture controller). By analysing the electrical activity coming from the muscles, software systems can perform hand gesture recognition (Benalcázar, 2017). This technology is also under investigation to anticipate the head movement (Sugiarto et al., 2021). However, recognition through sEMG is partially limited to static hand gestures, i.e., gestures that do not depend on overall hand movement but only on the movement of fingers or wrist. While sEMG sensors may be more comfortable than other wearables (e.g., gloves), compared to other interaction devices gesture recognition with sEMG devices can be inaccurate, decreasing user trust and hampering immersion and presence. (De Paolis, L. T., 2020). Further, like vision-based hand tracking and motion capture gloves, these devices lack any means of haptic feedback.

Figure 7: Armband sEMG sensor (Myo, by Thalmic Labs)

2.3.1.3 BODY MOVEMENT TRACKING

While previous approaches focused on allowing interactions with the VE only via the user's hands, complementary interactions can be achieved by employing low-cost, **vision-based motion capture technology** (MoCap) based on human pose estimation algorithms. Those algorithms may work on top of colour or depth streams, provided either by standard colour cameras (Cao, Z, 2019; Mehta, D., 2019) or commodity depth sensors (e.g., Microsoft Kinect Azure). Usually, algorithms based on colour streams are correct up-to perspective scale, in contrast to depth-based algorithms, which have access to the full 3D information. While in the past, depth-based pose estimation algorithms have been used in many popular X-Box games, their application in VR environments has not been exploited much, maybe because earlier VR base station technologies interfered with the depth sensors, hampering VR controller and headset tracking accuracy. With MoCap, the exact body movements of the users can be transferred to their virtual avatars or translated into meaningful actions inside the VE, opening for a lot of interaction possibilities (Mehta, D., 2019). Like hand gesture recognition, part of learnability, ease of use, and guessability of MoCap technology is left to the application designers, responsible for mapping the user's body posture and motion to rich VR interactions. Like vision-based hand tracking, vision-based MoCap lacks haptic feedback due to being a non-wearable technology.

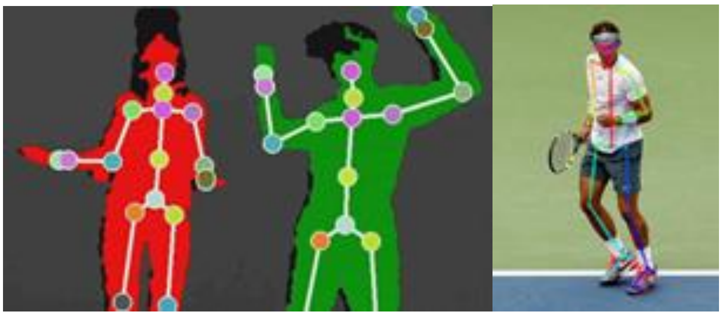


Figure 8: Depth - based human pose estimation / Colour based human pose estimation

Finally, one of the most immersive experiences in VR can be accomplished via wearing a **haptic suit** (e.g TeslaSuit (tesla, s.d.)). Modern haptic suits offer rich full-body haptic feedback, full-body motion capture, and physiological indicators. Those indicators, along with a dedicated software, recognise user stress level, emotional state, and key health indicators which enables the application to adapt to the user's mental and physical state. However, haptic suits are required to be available in different sizes to fit varying body shapes, essentially sharing the identical drawback with gloves. This fact, in addition to their significantly high price hamper their broad adoption.

Figure 9: Tesla-suit, full-body haptic suit

2.3.1.4 EYE TRACKING DEVICES

2.3.1.4.1 EYE TRACKING TECHNOLOGIES

Eye-tracking is a technique used to monitor a user's point of gaze and eye motion (Duchowski, 2017): see Figure 30 page - 70 -. The advantage is to measure the user's gaze location in a scene in real-time (Majaranta, 2012) and record visual system behaviours. Video oculography (VOG) (Zemblys & Komogortsev, 2018) is the most popular/common technique. VOG consists of gaze location estimation, which is carried out based on the pupil's centre tracking and the corneal reflection of a light emitted on the eye. This technique has the advantage of being non-invasive and in real-time but it has implementation difficulties (Majaranta & Bulling, 2014). These difficulties are: poor accuracy (Dalrymple et al., 2018), loss of tracking, the influence of content (luminance, colours, movements) (Binaee et al., 2016; Goldberg & Wichansky, 2003), and contextual effects related to the apparatus itself (nocebo effect (Wikipedia, s.d.)) (Höfler et al., 2018). Therefore, to ensure that the eye-tracker does not lose efficiency in tracking, frequent calibrations are necessary (B. T. Carter & Luke, 2020). Eye-tracking also requires high energy consumption, a determining constraint, primarily if implemented in HMDs.

With the integration of internal cameras in consumer HMDs (e.g. HTC Vive pro EYE, Lenovo Think Reality, Pimax Vision 5k Super & 8k, Varjo VR-3 & XR-3, VRgineers XTAL 5K & 8K, see D3.1, Appendix 1 for more details), ait opened way of designing new interaction modes based on eye-tracking has been opend. Such interactions are described in the following section. Other uses of eye-tracking to monitor user physiological state are described in section

2.3.1.4.2 GAZED BASED-INTERACTIONS

The gaze is a modality that offers many perspectives for human-machine interaction (Majaranta & Bulling, 2014). It is a fast and natural modality (Khamis et al., 2015), which, to a certain extent, allows us to quantify our centre of attention and anticipate our next action on the system (Hoang et al., 2008). However, it is more suitable for use as a passive modality. Indeed, an interaction modality is said to be active or explicit when the user initiates communication with the machine and constructs a command accordingly (e.g. by giving a command to the keyboard, the mouse...). Conversely, a modality is said to be passive or implicit when the system picks up on a user's behaviour, without the user necessarily explicitly seeking to communicate it (Clay A., 2009).

Explicit interaction through the gaze poses many difficulties, as eye movements are typically fast and subject to noise (Kumar et al., 2007). In addition, continuous measurement causes a "Midas touch" effect (Sibert & Jacob, 2000): is a user looking at an interactive element just looking at it or does he want to trigger it? The implementation of dwelling time fixations (typically of the order of 1000 msecs (Majaranta, 2012)) makes it possible to remove this limitation at the cost, however, of an interruption in the interaction process that is unpleasant for the user. The gaze is therefore much better suited to remain a complementary modality, supporting a main interaction modality to offer a more natural, intuitive and pleasant user experience. As a complementary modality, eye-tracking can speed up and improve interaction (Stellmach & Dachselt, 2013), refine user input (Kumar et al., 2007) and improve accuracy (Stellmach & Dachselt, 2012, 2013).

The gaze is a particularly important component of multi-person interaction, especially in a collaborative situation around a visually shared space (Brown-Schmidt et al., 2014; Clark & Brennan, 1991; Schober, 1993). The gaze thus makes it possible to perceive the attention and the degree of understanding of the interlocutor, to easily remove the ambiguities of language that may arise in the verbal exchange, and plays an important role in the management of speakers (Andrist et al., 2017). It is therefore an excellent option for those who want to make human-human interaction in a virtual world more fluid. It is also a modality that is perfectly suited to virtual reality, especially if it is used in a complementary way (in the sense of the CARE properties of multimodality (Nigay & Coutaz, 1997)) to gesture (Piumsomboon et al., 2017). Indeed, eye-tracking alone does not necessarily seem to be more effective than other interaction techniques (Qian & Teather, 2017).

2.3.2 IMMERSIVE ENVIRONMENTS

The Immersive Environment refers to the digital scene that the user enters when utilizing XR devices. The environment's design may reflect reality or present a complete abstraction, but the aim of users feeling immersed and present within the digital environment remains the same. Multiple considerations surrounding the environment can directly impact the user's behaviour.

This section will explore how behaviours can be affected directly by the immersive environment and what design considerations should be made to mitigate problems that may decrease focus, decision-making, and collaboration with other users.

2.3.2.1 THE EFFECTS OF VIRTUAL ENVIRONMENTS ON BEHAVIOUR

Blascovich, et al. (2002), highlight the advantages of using VR as an opportunity to explore people's behaviour in real-life situations while being able to control the inconsistency that the real-world environment may imply. Due to the realistic level of detail that immersive environments can provide, users commonly react to scenarios similarly to if they were occurring in reality, without risk exposure. Designing environments to mirror a user's expectations, such as placing a table in a meeting room, e.g., they would be expected to elicit common behaviours found within reality, such as users orientating themselves around the table (Rebenitsch & Owen, 2020). The design and layout of an immersive environment have been observed to impact the user's behaviour both for better and worse and remain an important aspect to consider.

Lee, Eden, Ewoldsen, Beyea, & Sanguk (2019), observed that participants in their immersive environment would often spend a large amount of time looking at "see-through" surfaces such as windows, rather than the objects in the environment intended for interaction. This may be due to several factors, including the common human desire to explore and the novelty of a virtual environment being a new experience. Lee, Eden, Ewoldsen, Beyea, & Sanguk (2019), found that objects that diverted from expectation also gained more attention than objects following their expected function. The authors found that "*the bouncing toilet and bed hanging would likely violate participants' anticipation and attract attention*." This would perhaps suggest objects within an immersive environment should match their real counterpart, except in instances where extra attention is necessary. Their research further suggests that environments should remain as clear as possible, avoid distraction, and direct focus to relevant objects and interactions within the immersive space.

The design of the environment can have severe implications on a user's health and behaviour. Meehan et al., (2003), utilized an environment made up of two different rooms to assess the behavioural differences the environment can provoke. The first room was described as a training room, where users could acclimatise to the digital environment. Adjoining the training room was a second room containing a virtual pit descending several metres. Despite participants being fully aware they were in a digital environment and physically safe, when introduced to the pit room, heart rate and skin conductance were consistently higher than when the participants remained within the 'safety' of the training environment. The psychological reaction to pit was demonstrated not only in the user's physiological reaction but also in some participants behaviour. Meehan et al., (2003), reported that many participants would be confident to walk towards the ledge, but some would tightly hug the wall for support. The significance of this research demonstrates possible precautions and considerations that need to be made when designing and developing the immersive environment. Ensuring the user feels safe within the environment is the first step in maintaining the user's rational thought.

2.3.2.2 THE TACIT FRAMEWORK

Territoriality, Awareness, Control, Interaction, and Transitions are the five key themes outlined in the TACIT design framework proposed by (Benyon & Mival, 2015), which focuses on user behaviour and experience in Interactive Collaborative Environments (ICEs). While their study focuses on physical collaborative environments, the same considerations can be applied to Immersive Environments; and by extension, the design of the INFINITYINFINITY Immersive Virtual Workspace.

"*Territoriality concerns spaces and the relationships between people and spaces*". Benyon & Mival (2015), found that the layout of the room greatly affected how people interacted within the space. A larger room with more freedom to move around and see things from other different angles seemingly improved collaboration. If a tabletop were present in the centre of the room, people would orientate themselves around the table, often viewing visualisations upside down rather than moving to see it from the correct perspective. During a brainstorming task, the assignment of roles was notably influenced by the participant's spatial position. The person sitting closest to the whiteboard would be designated as the penholder. Within a digital environment, it is expected that the same pre-existing psychological behaviours are likely to occur. The design and layout of an Immersive Environment are as essential to consider as a physical ICE. It should be noted that a purely digital environment can provide opportunities not available in a physical environment. For instance, visualisations could be displayed to users with the correct orientation regardless of their location, multiple users could be viewing the same data with the scene slightly differing for each.

The collaborative space within INFINITY is divided into two sections: a briefing space referred to as the hub and an analysis space referred to as the lab. By placing an object such as a table in the centre of the hub it can be expected that the users will naturally position themselves around it, drawing focus and attention to the middle of the room. Visualisations can be displayed centrally, and unlike reality, within the digital environment the orientation of the visualisation can directly match the orientation of the user. Likewise, designing the lab to be more open plan, allowing for more free movement would be expected to improve collaboration.

Awareness within the TACIT framework refers to the awareness of others within the environment. Attentions shift as users switch between individual and group tasks; however, participants remain aware of each other's activity through direct perception. It was noted that the surfaces within the environment affected collaboration differently. Users working individually on a wall screen would become silent and lose awareness of the room while working around a central table would create greater shared awareness.

Bringing users and visualisations in from the walls and towards a more centralised location within an immersive environment could improve collaboration between users. By looking into the room rather than away from it, collaborators can easily see each other's progress and changes to situations. This further highlights the importance of digital avatars within the digital environment to reflect the physical collaborators. More information on user representation can be found in section 3.7.3 page - 93 -.

In the context of INFINITY, it is anticipated that analysts will alternate between working both individually and collaboratively within the shared environment. By designing the environment to be as clear and open as possible, it will allow users to maintain peripheral awareness of the other ongoing tasks in the environment and according to Benyon & Mival (2015), would be expected to see improved collaboration. Considerations around the transparency of visualisation objects within the environment can also be assessed within INFINITY. The opacity of the objects can be adjusted to find a skewed balance between readability and an increased awareness of the room. Benyon & Mival (2015), describe control within the TACIT framework as "*the control of the software* *systems and social control of the collaborative activity*." Their observations found people would take turns to interact with devices to maintain control. For instance, one person would operate an interactive display at a time. In situations where screens were mirrored across multiple devices, awareness of the situation was improved, but control was negatively impacted as inputs from each user caused accidental conflict. Within a digital environment, there is potential that users are not viewing the same scene in complete synchronisation; e.g., displays may be orientated towards the individual user. The interfaces within the immersive environment should be designed in such a way as to highlight who is currently in control of an object to improve cooperation and collaboration while avoiding conflicting inputs from multiple users.

Interaction within the TACIT framework concerns "*how people interact with each other and how they interact with the activities they are undertaking. It is concerned with the user interfaces, with usability, accessibility and the articulation of tasks between collaborating individuals and groups*". They describe designing environments to a human scale, accommodating for "short arms, fat fingers and people's height". The same design practices can be applied to immersive environments to ensure high levels of useability, particularly across user interfaces. A digital environment provides additional opportunities to explore the effectiveness of interfaces that remain relative to the user's position, keeping valuable, and common items always within reach of the user.

Finally, transitions outline moving from one task to another. In terms of ICEs this may include moving from a physical task to digital and then back again. Emphasis is placed on the need for designers to focus on ease of transitions between two separated tasks. The same premise is equally important within an entirely digital environment. Transitions between tasks should be made as intuitively and efficiently as possible to prevent collaborators from becoming excluded.

INFINITY proposes to move users from the immersive virtual workspace to "breakout rooms" for more specialised tasks such as node graph analysis. It is highly recommended that precautions are made to minimise the difficultly and break in immersion that this may cause, ensuring transitions between spaces are intuitive and seamless as possible.

Considerations need to be made for the size of the environment, particularly in collaborative environments. Physical space needs to be large enough to accommodate multiple users but remains reasonable to allow efficiency. Studies in proxemics have been conducted to understand the need for personal space within virtual reality. Wilcox, Allison, Elfassy, & Grelik (2006), found objects moving towards a user induce negative psychological reactions the closer in the proximity the objects become. Not only did the user report discomfort, but skin conductance also increased.

Experiments by Llobera, Spanlang, Ruffini, & Slater (2010), identified that participants responded almost identically when approached by virtual objects or virtual people. Despite being aware they were within the safety of a virtual environment, typically, the users would demonstrate discomfort and naturally want to step out of the way. According to authors, this may be due to fear of object collision or a break in social norms in the case of the virtual person. Within collaborative environments, there are potentially many moving objects in addition to other users. Allowing space within the environment for users to move around, move objects, and pass naturally is essential to avoid unnecessary discomfort.

2.3.3 USER REPRESENTATIONS IN IMMERSIVE ENVIRONMENTS

Virtual Reality (VR) and especially Social VR allows several separated users to collaborate and interact in Immersive Virtual Environments (IVEs). The users are typically represented by avatars inside the IVEs to increase the sense of *presence* and *social presence*. The users are usually represented by a 3D avatar. This representation is modelling their interaction with the environment and distinguishing between different users, i.e., it serves as a proxy for the user and all their possible communication and interaction in the virtual environment.

In social VR frameworks, the different features and mechanics of the avatar, as well as its relationship and its interaction with the virtual environment constitute the *avatar system* (Kolesnichenko et al., 2019). There are many different aspects that need to be considered when designing avatar systems. In (Kolesnichenko et al. 2019) an extensive study for assessing the avatar design choices in social VR frameworks such as AltspaceVR (altvr, s.d.), Mozilla Hubs (Mozilla, s.d.), VRChat (hello.vrchat, s.d.), Facebook Spaces (Facebook, s.d.) (which has been discontinued to give its place to Facebook Horizon (Occulus, s.d.)), Anyland (Anyland, s.d.), High Fidelity (highfidelity, s.d.), and Rec Room (Recroom, s.d.) is presented. The authors interviewed key personnel from each company regarding the design choices behind their respective avatar systems and their features, which they called *affordances*. In this section,the commonalities and differences between different social VR frameworks in terms of avatar appearance, locomotion, social mechanics, personal spaces (i.e., VR spaces that only one user has access to), and the avatar's relationship to virtual identity (mostly correlated with appearance), are analysed

Avatar aesthetic features are mostly common to all the different social VR frameworks, with few exceptions supporting a greater variety of choices. This is mainly because social VR frameworks must run fluently and additionally support a vast number of participants. Therefore, the provided avatar assets are cartoon-like characters with limited appearance features or low detail human characters. Despite the avatar's realism, another factor that varies is its visible body parts. This factor ranges from avatars with full-body visibility (primarily for realistic avatars) to very minimal representations with only the avatar's head and hands visible. This variation is presented in Figure 10, and some examples of the appearance of avatars in different social VR frameworks are presented in Figure 11.

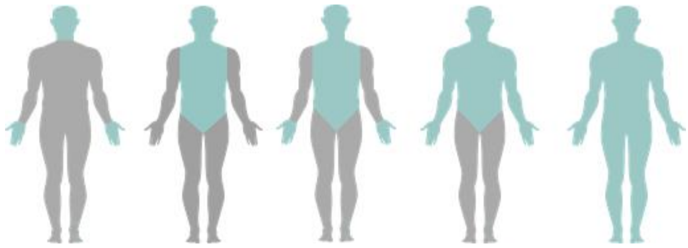


Figure 10: Variation of avatar appearance in social VR frameworks with increasing detail. From left to right: the avatar is composed of only the head and hands, the upper body and no hands, the upper body and the hands, the full upper body, and the full body (mostly used for realistic avatars).

Similar to their appearance, avatar locomotion and animation features are primarily standard in most frameworks. This is because VR hardware provides limited input via their respective controllers. Therefore, social VR frameworks mainly support only hand motion with pre-defined expression and body animations to increase immersion. However, some exceptions offer full-body motion via Inverse Kinematics (Peiper, 1968), but with the requirement of additional motion trackers on specific parts of the user's body.

Figure 11: Different avatar representations in social VR frameworks. From left to right: Avatars with upper body and no hands in Mozilla Hubs, avatars with upper body and hands in AltspaceVR, full-body cartoon and realistic avatars in VRChat, full upper body avatars in Facebook Horizon, full-body avatars in High Fidelity and upper body and hands avatars in Rec Room.

The main differences in locomotion between social VR frameworks relate to the participant's navigation inside the virtual space. Teleportation is one of the dominant forms of avatar locomotion, with the user deciding where to move via their platform's VR controllers. More specifically, High Fidelity, Rec Room, and AltSpaceVR use teleportation as the primary mode of navigation. On the other hand, users have the ability to walk in VRChat, while Facebook Spaces does not provide the ability to travel (McVeigh-Schultz et al., 2018). On most social VR frameworks, walking is implemented using the joystick of the VR controller. The user is able to move forward or backward by pointing the controller's joystick to the respective direction, while turning is achieved by looking at the desired direction. This travelling scheme is effective as it prevents the users from getting tangled up by the HMD's display cord, and additionally provides an intuitive way for changing directions (i.e. by looking at the desired direction) (Sherman, 2019). Nevertheless, the most popular design practice for teleportation is the *parabolic pointer* (Figure 12), which allows the user to teleport on top of elevated objects in relation to the avatar's position in 3D space (Kolesnichenko et al. 2019). The main advantages of this type of scheme is that the user's exprerience minimal motion sickness and it is very easy to learn and use, however there is a possibility of disrupting the user's immersion (Sherman, 2019). Finally, a unique locomotion mechanic supported exclusively in VRChat, is *third person walking*, which helps minimize motion sickness (which is present in first-person VR experiences) and in situations when the user's desire to assess the performance of their avatars.

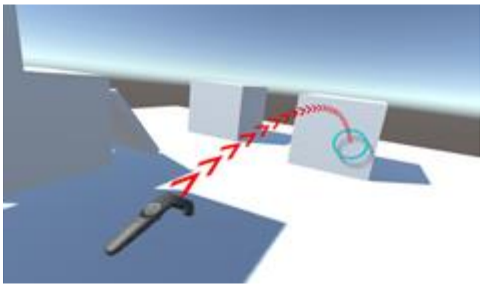


Figure 12: Teleportation via parabolic pointer (Autodesk-Stingray)

The locomotion mechanics described above are evaluated against a set of criteria for measuring effective travel schemes in VR worlds (Sherman, 2019).

Social mechanics are the functionalities and features that allow the users to perform their social skills. These, may include starting or ending virtual friendships, participating in group activities, or expressing their emotions through talking or non-verbal expressions. Most of these functionalities become available to the users through menus via each framework's Graphical User Interface (GUI), or by (controller-based) gestures. For example, in High Fidelity, a handshake with another user results in an explosion of pixels, indicating that the two users have become friends. The same feature is available via a fist bump in Rec Room.

Non-verbal expressions are usually accessed through menus and result in animating the user's avatars with predefined expressions or displaying unique widgets on top of the user's avatar. Moreover, social VR frameworks provide the ability to talk with other users, resulting in animating their avatar's lips. A notable feature that Rec Room offers is spatial audio, which compliments their emoting system and is meaningful in small group settings. However, when more people are involved, it is challenging to identify who is speaking. To address this challenge, designers introduced the *speech lines* feature, which displays a bubble over the user's avatar to identify who is speaking.

The user's virtual identity is strongly correlated with their avatar's appearance. Each framework offers customization features and representation aspects that are strongly related to the user's virtual identity and the perception of others. However, designers still struggle to give the freedom the users should have to take on the form they want. For example, Mozilla Hubs gives its users the ability to upload their own assets and use them for avatars. In Rec Room, users can earn rare items from accomplishing certain quests and display them on their avatars. Additionally, Facebook Spaces offered an image recognition feature, with which the users could create an avatar resembling their real selves.

In conclusion, the design approach to an avatar system in social VR depends on the high-level goals and priorities of the creators. The main factors that will contribute to its design are the framework's goals on user capacity, which can determine the level of detail of the utilized avatar assets, and the general purpose of the platform, from which locomotion, or social functionalities and features can be established. A detailed listing of all the identified affordances of avatar systems in social VR frameworks is presented in Table 3.

Table 3: Variety of avatar system features in different social VR frameworks according to Kolesnichenko et al. (2019)

	Facebook Spaces	Mozilla Hubs	High Fidelity	Rec Room	AltspaceVR	Anyland	VRChat
Embodied Locomotion	✗	✓	✓	✓	✓	✓	✓
Other Navigation Mechanics	✗	✗	✓	✓	✓	✓	✓
Create Custom Worlds	✗	✗	✓	✓	✓	✓	✓
Default Avatar Selection	✓	✓	✓	✓	✓	✗	✓
In-world Avatar Customization	✓	✗	✓	✓	✓	✗	✗
Import Avatar	✗	✗	✓	✗	✗	✗	✓
Share Custom Avatar	✗	✗	✗	✗	✗	✓	✓
Humanoid Avatars	✓	✗	✓	✓	✓	✓	✓
Nonhumanoid Avatars	✗	✓	✓	✗	✓	✓	✓
Photo-generated Personal Avatars	✓	✗	✗	✗	✗	✗	✗
Built-in Facial Expressions	✓	✗	✗	✓	✗	✗	✓
Emoting System	✓	✗	✓	✓	✓	✗	✗
Personal Space Mechanics	✓	✓	✓	✓	✓	✓	✓
Embodied Social Mechanics	✓	✗	✓	✓	✓	✗	✗
Unique features	Image recognition	Import Media File in VR	Platform Creation Tools	Group Travel	Cross-platform Support	In-world Creation Tools	Import Custom Avatar

2.3.4 NATURAL USER INTERFACE AND MULTIMODALITY

The virtual reality paradigm (as well as the augmented reality paradigm) is based on a way of presenting information that breaks with traditional displays. This break with the traditional implementation of the interaction loop involves the use of new interaction modalities, such as movement, adopted by the consumer headsets on the market.

Virtual reality, through the immersion it offers, is an ideal terrain for the use of "natural" interaction (Natural User Interfaces or NUIs) (Wigdor & Wixon, 2011). NUIs aspire to an "invisible" interface, or at least one that becomes invisible after learning; the "natural" aspect refers to the organic, instinctive properties of the interaction. Natural interaction is therefore based on the intrinsic capacities of humans for communication and manipulation. As such, it encompasses many fields, such as interaction through movement; tangible interaction, which makes it possible to use the human capacity to manipulate tools; the use of natural language for interaction; voice recognition; eye tracking; haptic interaction, etc. But how to design such interactions? There is a lack of tools for design. Some thoughts are emerging, counterpointing certain preconceived ideas: for example, Wigdor and Wixon, in their book Brave NUI World, defend the notion that the design of natural interactions should not necessarily be based on equivalents in the real world (which would truncate much of the interest of virtual reality), nor on a desire to exempt the end user from any familiarisation with the system (Wigdor & Wixon, 2011). On the contrary, such interactions should propose a process of familiarisation on the part of the user, who would thus gradually reach an expert mode. For example, travelling in a 3D Virtual Reality map can be done by flying, jumping or teleporting (Lütjens, Kersten, Dorschel & Tschirschwitz, 2019).

The use of multimodality could be part of the solution to the problems of designing natural interactions. Indeed, multimodal interaction consists in coupling various communication channels between the user and the system for a given task. Humans are naturally deeply multimodal creatures in their communication (Oviatt et al, 2003a; 2003b; Clay, 2009). Depending on the task under consideration, different modalities (or combinations of modalities) can thus be favoured to elicit in the user this sensation of organicity and intuitiveness. Bolt's seminal work on multimodality (Bolt, 1980) is a perfect example of combining input modalities (voice and gesture) to achieve a natural result. It is also possible to take a much finer view of multimodality, for example by considering different body modalities (use of the whole body or a few fingers for example), or even by introducing modalities localised in a certain area of the action space. This fine vision of multimodality has already been established in previous works (Clay, 2009), and corresponds to the current multiplication of specialised devices. The joint use of these different devices is a key point in the development of natural interaction, in connection with ubiquitous, mobile, and wearable computing. Today's natural interactions are still often limited by hardware issues. The use of multimodality makes it possible to overcome these limitations at least in part by using devices that are adapted to the task in question. Moreover, the field of multimodal interaction offers a design space that has been proven (Nugay et al., 1993; 1997).

A collaborative meeting situation in virtual reality involves two types of interaction. Firstly, Human-Human Mediated Interaction (HMI) corresponds to the interaction between the different users, through a technological system (here, notably through avatars). Technologically mediated communication is necessarily degraded compared to direct communication. The design should thus seek for interactions that will make the interaction between two users more natural. Secondly, users will have to interact, in a classical way, with the virtual world in which they will be immersed. The design should also seek for interactions that will make the relationship between users and the virtual world more fluid, especially with the data and their representation.

2.4 USE OF XR AT WORK

2.4.1 LEAS' WORK AND COGNITIVE PROCESS INVOLVED

Cognition is the studies of the cognitive process, how does the brain work to do some tasks, such as work, collaboration, attention, memory etc. Examples of LEAs activities comprise collaborative activities and data analysis activities. They involve problem solving cognitive processes including abstraction, searching, learning, decision making, inference, analysis, and synthesis, based on internal knowledge representation by the object–attribute-relation (OAR) model. Knowing this numerous process allows us to target the user cognition need.

Problem solving and decision-making are key elements in human activity (Hernandez, Karimova, & Nelson, 2017). LEAs' work can lead to risk-based decision-making (Lemaire, 2006). Here, the decision-maker must choose between a safe option (low reward or low option with high reward) or uncertain decision-making (uncertain outcomes).

This decision-making is a mental process that involves several distinct but interdependent operations, allowing an individual to choose between several of these options (Allain, 2012): (1) Definition of the purpose of the decision; (2) Information search; (3) Analysis and organization of information deemed useful; (4) Elaboration and evaluation of decision-making possibilities; (5) Decision making.

For each of these steps, authors have identified cognitive processes at work that can help, or undermine, decision-making and problem-solving. Because of the diversity of cognitive processes involved in problem-solving, there are as many resolution techniques as cognitive processes involved, making it possible to solve the problem (direct facts; heuristics; analogy; deduction, etc.). Wang and Chiew (2010) have developed a multi-layered reference model (LRMB) that highlights the links between cognitive, metacognitive and decision-making processes.

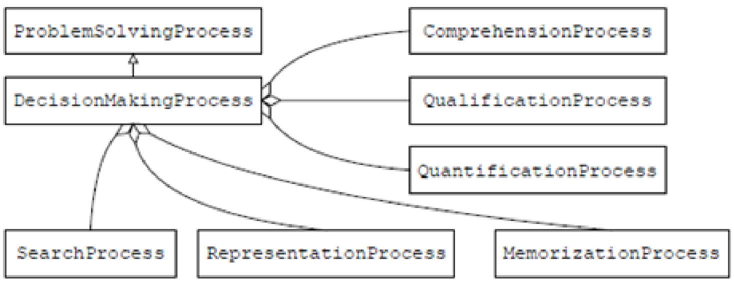


Figure 13: Relationship between different cognitive processes and decision making in LRMB model (Wang & Chiew, 2010)

It can be appreciated the importance of each phase, including understanding and representation. Indeed, several authors have been able to demonstrate that it is essential for the individual to be able to properly represent the situation, to understand it and make an appropriate decision, to have an awareness of the situation (Endsley, 1995) and a mental model of the right and appropriate situation (Johnson-Laird & Byrne, 1991).

A mental model is the internal representation of the situation made through the given elements and that can be shared (Converse, Cannon-Bowers & Sala, 1993). Therefore, situational awareness is an internal mental model based on the representation of the environment, the individual's knowledge about what surrounds him, its understanding and projection of their state in the near future (Endsley, 1988). It is important to note that for the same information entry, situational awareness may vary, depending on individual's cognitive, metacognitive or motivational activity.

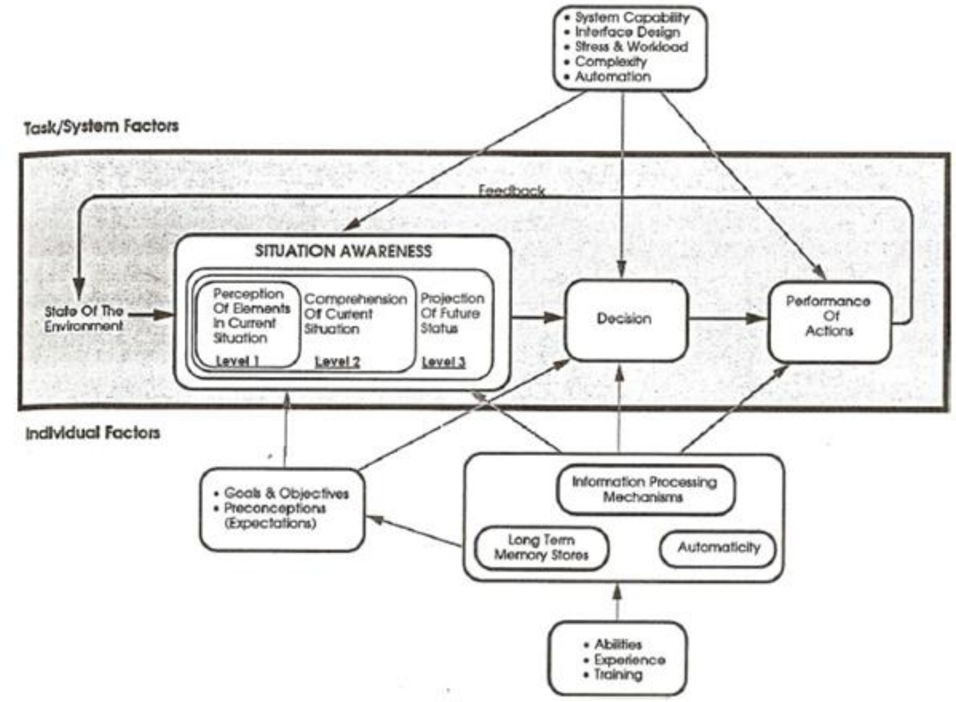


Figure 14: Situational awareness and decision making on dynamic situation (Endsley, 2000)

The Situational Awareness (SA) model is action-oriented. The elements that need to be understood are determined by the operator's objectives. Endsley (2000) describes the acquisition of SA as the articulation of three processes:

- The environmental observation phase, which consists of perceiving the states, attributes, and dynamics of environmental elements.
- The phase of understanding the current situation, analysis and understanding of the meaning of the elements, in the light of the objectives pursued.
- The projection phase of the future states: the individual must project a mental model of behaviour (direct facts; heuristics; analogy; deduction, etc.) on the identified elements and understand them to predict the evolution of the situation.

Thus, situational awareness is a dynamic personal construction; from a situation, an analyst creates an "operational picture" from external sources (tools, data) and internal sources (objectives, motivation, expertise) to emerge with a mental model of the situation and action. In this regard, in his "Observe Orient Decide Act" (OODA) decision-making model, Boyd (1997) describes the stages of decision-making. He highlights the importance of situational awareness, taking shape through "operational pictures," representing the state of the environment, leading to the SA.

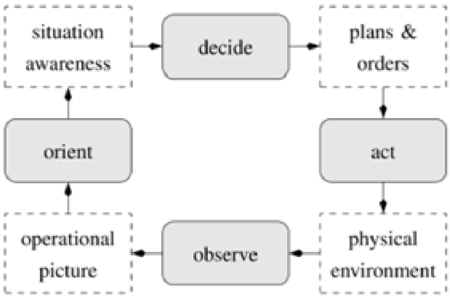


Figure 15: OODA model (Boyd, 1992) In Kabil et al. (2019)

Following the need to analyse cybersecurity activity, an adaptation of the SA was proposed to the cyber domain, CSA (Cyber situation Awareness) by Onwubiko (2016). The CSA concerns the linkage between data analysis and visualization tools and cybers analysts' cognitive capacities and processes, human-machine, and human-human cooperation. To develop the most accurate and just situational awareness possible.

A critical point emerges during a review about CSA by Kabil & al. (2019). CSA did not exist in a collaborative way, even if SA is recognized to have a substantial impact on decision making. The ability to share SA can be the critical point of collaborative activities. Shared representation, space, and presence are elements recognized to impact collaboration in virtual environment (Zyda & Singhal, 1999).

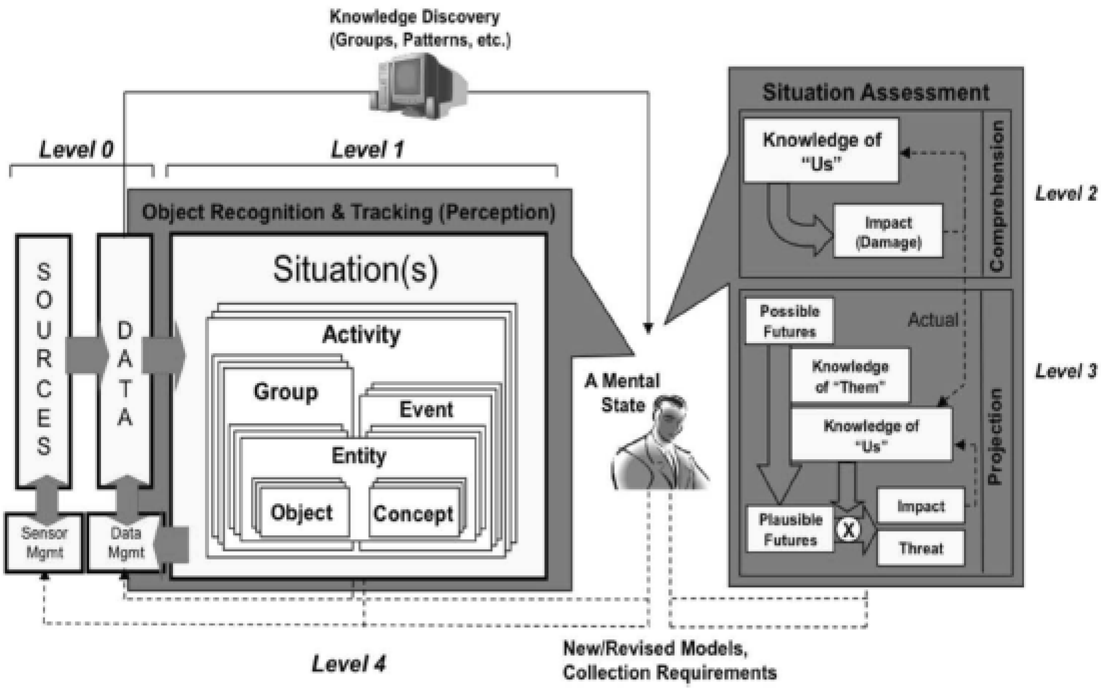


Figure 16: CSA model, with external data and cognitive process (Tadda & Salerno, 2010)

Wellbeing is a complex process involving cognitive processes, affect and other elements. It is important to think of the health and wellbeing of the worker with the introduction of new innovative tools at work and also because it impacts their productivity.

Wellbeing is equilibrium/homeostasis between resources and challenges. Resources and challenges (Hendry & Kloep, 2002), are the elements that can affect the individual's equilibrium; tipping the seesaw from side to side, supporting (Csikszentmihalyi, 2002) the updated concept of 'flow'. Kloep et al. (2009, p. 337) described: "Each time an individual meets a challenge, the system of challenges and resources comes into a state of imbalance, as the individual is forced to adapt his or her resources to meet this particular challenge". In essence, stable wellbeing is when individuals have the psychological, social, and physical resources they need to meet a particular psychological, social and/or physical challenge. When individuals have more challenges than resources, the see-saw dips, along with their wellbeing, and vice-versa.

Figure 17: Definition of wellbeing (Dodge, Daly, Huyton & Sanders, 2012)

Can the immersive environment help the worker to have more resources to respond to the challenges? Indeed, Smith et al. 1995 found that police (and air traffic controllers and nurses) had high decision-making latitude but dealt with a multitude of variables and simultaneous sources of stress, and it impacted negatively on their well-being. To explain it, the author identified three major areas related to the health and wellbeing of workers: (1) hazardous work settings related to illnesses and diseases; (2) **the impact of work condition to stress;** and (3) the specific illnesses and the relation with personality characteristics or types of work environments. The point two is related to the condition of work and what we will address. We are going to focus on the use of immersive environment that can be, or not, a response to the work condition, and have an impact on cognition health and wellbeing. We will see why in the rest of the document.

2.4.2 COLLABORATION AND COGNITION

Collaboration is one of the activities carried out during teamwork with the aim of problem solving and decision-making. It is the sum of joint and interdependent activities to achieve a common goal (Hauber 2008), such as abstraction, inference, data analysis, and synthesis. During the collaboration, employees make a joint effort to align and integrate their activities in a "transparent" manner without interruption (Schmidt 2002). One of the main central aspects of the INFINITY project would be to make more accessible knowledge, shared information, and the recognition of teamwork expertise (Hinsz et al., 1997). The virtual environment can be interesting because it can help reduce cognitive load involved in this activity and facilitate construction of good situation awareness and its sharing.

Because teamwork is not just the sum of individual work but also synchronized work, the production made by the teamwork (the results) and the process that leads to this result (Annett & Stanton, 2000) should be studied. Being the work of LEAs confidential, first we should understand how the process of collaboration that leads to a result. In this regard, Amenities defines four components impacting a collaborative system: the group (groups, roles, and actors), cognitive processes (self-regulation, motivation), interactions (protocols, devices, media), and information (resources, documents, messages).

Regarding the group, there are different groups in the INFINITY system, focusing on different tasks and events. In each group, different roles exist, with local experts involved, LEAs from different MS with different expertise; external experts with limited roles and access; decision makers and chiefs. Each role brings different goals and access to the INFINITY system, which have to be considered to achieve good collaboration.

Concerning the cognitive process, as discussed before, for problem-solving each member of the team has to develop a good situation awareness, a good understanding of the situation. But for teamwork, need a shared mental model (SMM) is needed (Cannon-Browers et al., 1993). An SMM is a mental structure of knowledge used by humans to organizes information, predict events, and interact with others and the system (Gentner and Stevens, 1983; Rouse & Morris, 1986). The SMM allows team members to coordinate their behaviour and activities by understanding and monitoring the team member's activities. If they share a mental model, they also share and understand the other needs, tasks, and progress (or delay). An SMM is a shared vision of the environment and the situation. Two types of SMM have been identified: task-mental model, referring to the representation of the tasks to achieve and sub-tasks involved in it; and the team-mental model, referring to the awareness of the member roles, expertise, work habits etc.. The task-mental model members have to share the same information on interactions (protocols, device, media) and information (resources, documents). And on a Team mental model, they have to share information related to the group (roles, group…) and cognitive processes (motivation, way of work, situation awareness). These two SMM can lead to a common referential of the collaborative activities.

Today, with the advent of digital technology and the health context, teamwork is more and more in remote contexts. Remote collaboration, at different locations and at different times (asynchronous), or not (synchronous), are becoming more common (*more detail in deliverable 3.1*). Virtual reality appears a viable technology for collaboration and working. Therefore, potential impacts on collaboration efficiency, well-being, and health, whether positive or negative, need to be addressed.

3 ERGONOMIC RISKS OF VIRTUAL REALITY FOR LEAS

3.1 HIGHLIGHTS OF ERGONOMICS RISKS WHILE USING VR AND ASSOCIATED ISSUES

Virtual reality replacing part of current work occurring with PC (mouse and keyboard) is increasingly considered both by the industry and scientists. For instance, "Infinite Office" by Oculus (Oculus, 2020) or vSpatial (*vSpatial*, s. d.) aim at providing office-like interactions in VR. An article published in Road to VR identifies 34 apps for work and training (close to work situations) (Lang, 2020). However, many scientific issues regarding interactions and interfaces remain to using office-like tasks in VR. Most ergonomic issues are still open research questions. Contributions start to analyse the various tasks that an average worker fulfils using a PC, transposed to VR: spreadsheets (Gesslein et al., 2020), text entry (Knierim et al., 2018; Speicher, et al., 2018), editing (E. Kim & Shin, 2018), reading (Baceviciute et al., 2021) and information retrieval (Schleußinger, 2021).

We focus primarily on one position within LEAs: crime analysts (Green & Rossler, 2019; Piza & Feng, 2017). They are the primary users of INFINITY. Crime analysts are the workers providing "*systematic analysis of crime for identifying and predicting risks and efficiently directing police resources*" (Burcher & Whelan, 2019; Sanders & Condon, 2017). This analysis heavily depends on data, especially in the fight against cybercrime (Neto, 2017; A. Kabil et al., 2018; Michel et al., 2018; Bhalerao et al., 2019; R. Damaševičius et al., 2020; Robertas Damaševičius et al., 2019; Koa et al., 2019) and terrorism (Badia, 2020; Fujita et al., 2020; Wells, 2017). The current work of analysts takes place happens in an office for which transposition in VR has been imagined already for usual tasks (Grubert et al., 2018). Visual analytics in VR seems promising and as efficient as the current media (Kraus, Miller, et al., 2020), sometimes out-performing them (Erra et al., 2019; Kraus, Weiler, et al., 2020). Previous works investigate visual analytics, data processing, graph creation, and reading in VR (Alexandre Kabil et al., 2020; Stevens & Butkiewicz, 2019). But not restricted to VR, spatial interfaces for 3D visualization still require more developments (Besançon et al., 2021). Çöltekin et al. (2020) highlight the possible use of XR in Geographic Information Science to gather multimedia geolocalized data. Çöltekin et al. (2020) emphasize the consideration of mental workload and visual fatigue as research priorities in human factors for XR with the aim to customize and personalize interfaces. VR as a new media could intrinsically change our approach of some tasks. For instance, ethical decision-making with moral dilemmas in VR seems to foster utilitarian decision-making, amplifies biases like sparing juveniles and seeking retribution (Niforatos et al., 2020). Therefore, human factors/ergonomic risks need to be addressed.

Introducing VR at the workplace leads to considering side effects, induced stress, and mental workload to encompass the safety and health of LEAs workers (Olson et al., 2020). Reviews of HMDs in the work environment already point to issues like cybersickness (Khakurel et al., 2018). Legislations and good practices supervise current screen use to protect workers. Although it has no legal effect, Section II, Article 3, Paragraph 1 of the *Council Directive on the minimum safety and health requirements for work with display screen equipment* from the OSHA, states (European Agency for Safety and Health at Work, 1990):

"Employers shall be obliged to perform an analysis of workstations in order to evaluate the safety and health conditions to which they give rise for their workers, particularly as regards possible risks to eyesight, physical problems and problems of mental stress."

To encompass risks of side effects in using VR for LEAs, we describe the most probable issues in general, and in particular in the context of working in VR, and report on the state-of-the-art approaches in measuring cybersickness, visual fatigue, muscle fatigue, acute stress, and mental overload. Each side effect issue, after a general presentation, is contextualized within typical tasks that users are susceptible to fulfil in VR with the INFINITY platform, namely:

- Gathering and processing data from various sources
- Creating graphs and data visualization (e.g., maps)
- Exploring and analysing data
- Viewing several media (text, images, video, maps)
- Entering text and editing documents
- Reading texts
- Creating presentation materials
- Conducting meetings (briefings, data presentation…)
- Collaborating with other users in a shared VR environment (and object views)
- Moving around the virtual environment or graphs
- Making shared decisions for ongoing investigations (meetings)

These tasks take place in two case scenarios: In fighting cybercrime (Payne, 2019) and in counter-terrorism in the aftermath of a terrorist attack, during which an investigation implies time pressure and high performance. Those scenarios in LEAs work elicit possible risks regarding physical and psychological health. On top of being a concern for worker's health, those risks could reduce task performances during the use of INFINITY. We concentrate on what can occur while workers are immersed (see Table 4 page - 38 -). However, that episodic exposure to VR side effects could have consequences that scientific literature has not yet studied. Ultimately, those side effects could be chronic and turn to be occupational health and safety hazards. Therefore, we propose a state of the art of potential risks regarding VR for LEAs work.

It is worth noting that VR is also introduced at several levels of an investigation or police work: crime scenes-related suspect interrogations (Norman et al., 2020), crime scene reconstruction (J. Wang et al., 2019), virtual crime scene simulation to train investigators (B. Liu et al., 2017), and forensics information for incident scene walkthroughs (Reichherzer et al., 2018; Sieberth et al., 2019).

Table 4: List of ergonomic risks identified associated with immersive environment

VR side effects	Acute stress	Mental overload
Cybersickness	Public speaking	Task load
Visual fatigue	Techno-complexity	Time pressure
Muscle fatigue	Techno-overload	
	Time pressure	
	Task difficulty	
	Distressing material	
	Noise	

First, VR side effects that can arise, no matter the task, are introduced, focusing on using VR at the workplace: cybersickness, visual fatigue, and muscle fatigue. Second, it is explained how the INFINITY platform could provoke acute stress with technostress, noise, exposure to distressing material, task difficulty, time pressure, and public speaking. Third, the mental overload risks are explained. Fourth, sensors and questionnaires to measure cybersickness, visual fatigue, stress, and mental workload are proposed. Fifth, the way how these states are connected and impact each other's is acknowledged. Sixth, the issue of distinguishing cybersickness from visual fatigue, from acute stress and mental workload is described.

The intention is to provide a viewpoint relying on ergonomics methods about what working in VR implies for LEAs covering typical tasks within each use case scenario. By making this inventory, the objective is to rationally consider the risks of VR use for LEAs workers and include their consideration in the design process of the INFINITY platform.

Table 5: Key ergonomics risks while using VR and related issues

Cybersickness	VR provokes cybersickness. This state is still studied and requires more experiments as well to reach a theoretical consensus. 40 factors could influence cybersickness
Visual Fatigue	VR provokes visual fatigue, more than other screen uses (computer screen, tablets, smartphones) mainly due to vergence-accommodation conflicts. This state needs more experiments and clarifications on how it differs from cybersickness. 14 factors could influence visual fatigue
Muscle fatigue	VR provokes muscle fatigue and musculoskeletal discomfort heavily depending on tasks and interactions. 15 factors could influence muscle fatigue
Stress	VR potentially leads to acute stress because of technostress, noise, exposure to distressing material, task difficulty, time pressure, and public speaking
Mental overload	VR potentially leads to mental overload mainly depending on task load and time pressure but also intrinsically on interactions and the interface with the virtual environment

Combining physiological data allows the measuring those states (Eye tracking, ECG, EDA), behavioural data (time at a task, errors at the task), subjective data (questionnaires such as STAI-6 for stress, VRSQ for cybersickness and visual fatigue, NASA-TLX for mental workload) and user-profile questionnaires (previous uses of video games and VR, motion sickness susceptibility, age, gender, stereoscopic visual ability, body mass index, stress, and anxiety traits). However, VR side effects, acute stress, and mental workload could vary or covariate depending on the presence of each state: they might be tangled as they all imply anatomic nervous system activity.

Distinguishing each state is necessary before being able to monitor it while using VR. Yet, these tangles make it challenging to differentiate each state based on live detection and psychophysiology. Running experiments in-lab and at the workplace (with LEAs) is necessary to warranty safe use of VR and write clear recommendations. This will allow considering real-time adaptation of the INFINITY platform depending on user's state (presenting cybersickness, stressed, presenting mental overload) but also specific path (discovery of VR little by little, short exposure duration, easy tasks) for identified persons more susceptible to VR side effects (Task 7.6).

3.2 VIRTUAL REALITY SIDE EFFECTS

Scientific literature has documented side effects consequent to VR use since its debut (Keller & Colucci, 1998; Cobb et al., 1999; Nichols, 1999; Nichols & Patel, 2002; Sharples et al., 2008; Melzer et al., 2009; Fuchs, 2017, 2018; Souchet, 2020). Using VR in everyday work is little investigated in overviews (Jerald, 2015; Slater & Sanchez-Vives, 2016). However, graph exploration is one evoked scenario (Bellgardt et al., 2017), and the concept of "immersive analytics" is a growing interest (Skarbez et al., 2019). Using VR in everyday work falls into current normalization ISO 6385 "Ergonomic principles in the design of work systems," and the EU-OSHA already identified VR side effects risks in a brochure on digitalization (*Digitalisation and Occupational Safety and Health*, 2019). Therefore, there is a strong need to encompass VR side effects in everyday work to provide guidelines regarding such normalization or future regulations. Above all, making sure of the user's wellbeing is necessary.

The portmanteau word Cybersickness usually encompasses VR side effects (Descheneaux et al., 2020; Kemeny et al., 2020; LaViola, 2000; Moss et al., 2008; Saredakis et al., 2020). However, Cybersickness concentrates on visual-vestibular-proprioceptive mismatch visually induced (not physically). Symptoms are similar to motion sickness, which includes only part of VR side effects (M. S. Dennison & Krum, 2019). Those side effects are real problems that elicit negative user experience (Lavoie et al., 2020; Somrak et al., 2019). Concretely, users might be sick or suffer from side effects that would harm their well-being. Furthermore, it could jeopardize VR adoption even within the scope of the INFINITY project.

This section aims at offering a state-of-the-art of known main side effects consequent to VR use. First, we tackle **cybersickness**, then **visual fatigue**, and, finally, **muscle fatigue**. It is worth noting that we mainly concentrate on acute symptoms, not chronic ones, based on repeated VR use, since no study (to the best of our knowledge) directly address medium to long-term side effects.

3.2.1 CYBERSICKNESS

3.2.1.1 CYBERSICKNESS OVERVIEW

The following symptoms characterize cybersickness (Bockelman & Lingum, 2017; E. Chang et al., 2020; Davis et al., 2014; Descheneaux et al., 2020; Lawson, 2014; Nesbitt & Nalivaiko, 2018; Rebenitsch & Owen, 2016): visual fatigue, headache, pallor, sweating, dry mouth, full stomach, disorientation, dizziness, ataxia (movements coordination), nausea and tiredness. During the first popularization phase of VR in the 90s, there was optimism about our ability to "cure" Cybersickness (Biocca, 1992). However, thirty years later, the issue still exists, as documented by the latest overviews (Stanney, Lawson, et al., 2020). Cybersickness arises no matter the HMD (Yildirim, 2020). Therefore, despite HMD technical improvements, cybersickness is not likely to disappear anytime soon (Gallagher & Ferrè, 2018).

Several competing theories are at stake to explain and predict the cybersickness phenomenon (Palmisano et al., 2020; Stanney, Lawson, et al., 2020). The sensory conflict theory of motion sickness (or sensory cues conflict) is the widely accepted theory (Lackner, 2014; Stanney, Lawson, et al., 2020). It states that: "*passive movement creates a mismatch between information relating to orientation and movement supplied by the visual and the vestibular systems, and it is this mismatch that induces feelings of nausea*" (Colman, 2009). As Watt (1983) remembered, Reason (1978), in his description of the theory, explains that motion sickness results when there is a mismatch between predicted and actual sensory inputs. Such predicted sensory feedbacks allow perceptual constancy in a human's natural environment. But within the virtual environment, due to sensorimotor conflicts (see section 3.2.2 page - 43 -), this constancy is disturbed (R. Patterson et al., 2006; R. Patterson, 2009). Most conflicts in virtual environments are visually induced (Rebenitsch & Owen, 2016). Our probabilistic brain, which seems to rely on predictive computation to perceive, process, and interact with the natural environment (Alais & Burr, 2019; Diaz et al., 2013; Mahani et al., 2017; Pouget et al., 2013; Van den Berg et al., 2015; Walsh et al., 2020), is facing inconsistent and unreliable cues from virtual environments. We hypothesize that these sensorimotor conflicts seem to provoke strategies from our brain to address unpredictability (E. S. Young et al., 2020). Our brain, via error minimization, is reweighting each sensory signal (Gallagher & Ferrè, 2018) to reduce unpredictability. It induces symptoms described under the portmanteau word Cybersickness. However, the exact psycho-physiological causes and the most parsimonious theory are not consensual to explain cybersickness (Davis et al., 2014; Descheneaux et al., 2020; Nesbitt & Nalivaiko, 2018; Stanney et al., 2020; Weech et al., 2018). It implies that the predictive power of current theories of cybersickness is inconsistent, and little understanding of individual variations (symptoms magnitude and probability of suffering from it) is provided (Nooij et al., 2017; Palmisano et al., 2020). Therefore, there are debates on models describing and explain cybersickness.

Two aspects of cybersickness research meet/find a consensus to date:

1) a unifying theory is still missing; hence more contributions under each competing prediction are needed
2) various strategies exist to tackle cybersickness: prediction, live detection, real-time cues changes in the virtual environment, adding sensory-motor "noise" to alleviate conflicts, stopping immersion etc. To deploy and assess each strategy, objective and subjective measures are necessary.

Hereafter, we describe cybersickness occurrence based on the current state of the art.

3.2.1.2 CYBERSICKNESS OCCURRENCE

According to Stanney, Lawson, et al. (2020), at least one-third of users will experience discomfort during VR usage, and 5% will present severe symptoms with current HMDs generation. Rebenitsch and Owen (2021), following Laviola (2000) and Davis et al. (2014), list three types of factors affecting VR experience and cybersickness.

Table 6: Possible factors inducing cybersickness based on Rebenitsch and Owen (2021)

Demographics	**Hardware**	**Software**
Experience	*Screen*	*Movement*
Experience with a real-world task	Resolution/Blur	Rate of linear rotational acceleration
Experiences with a simulator (habituation)	Horizontal and vertical field of view	Self-movement speed and rotation
Video gameplay	Weight of the display	Vection
Duration	Display type	Altitude above terrain
	Lag variance	Degree of control

Physical attributes	*Tracking*	*Appearance*
Eye dominance	Method of movement	Screen luminance
Stereoscopic visual ability	Calibration	Color
Postural stability	Position tracking error	Contrast
History of headaches/migraines	Tracking method	Scene content or scene complexity
Body mass index	Head movements	Global visual flow
		Orientation cues
Demographics	*Rendering*	*Stabilizing information*
Age	Stereoscopic rendering	Focus areas
Gender	Inter-pupillary distance	The ratio of virtual to real world
Ethnicity	Screen distance to the eye	Independent visual backgrounds
Vision correction	Update rate	Siting versus standing
History of motion sickness		
Mental attributes	*Non-visual feedback*	
Concentration level	Type of haptic feedback	
Mental rotation ability	Ambient temperature	
Perceptual style	Olfactory feedback	
	Audio feedback	

We rearranged Rebenitsch and Owen's (2021) factors into demographics (former individual), hardware (former device factor), and software categories (former task factor) compared to Davis et al. (2014). Forty factors influence cybersickness.

The documented higher risks of symptoms in women (the gender factor in demographics, see Table 6) in past works could be due to general ergonomics of current HMDs. The HMD's interpupillary (IPD) range of adjustment mismatch user's IPD and the headset themselves don't fit the user's head when they have a small stature, 35% of the time for female and 16% for males with the HTC Vive (Stanney, Fidopiastis, et al., 2020). Stanney et al. (2020) call for HMD adjustable lenses matching more than 99% of IPDs in the general population by ranging from about 50 to 77 mm (see also section about visual fatigue occurrence). But practically, women are more susceptible to cybersickness because of the impossibility of matching lens distance with IPD. However, there is no consensus about gender differences (Grassini & Laumann, 2020).

Latency or lag can impact cybersickness, but to date, the magnitude is still unclear as experiments are drastically different (latency measures, paradigms…) (Stauffert et al., 2020). Rebenitsch and Owen (2021) also point out that the initial factor of lag has been determined with old apparatus and argue that occurrences with new HMDs are less likely due to better performances.

Cybersickness increases with exposure time (Mark S. Dennison et al., 2016). The duration factor (Demographics, experience in Table 6) is widely pointed out as one of the main contributors to cybersickness in appearance and magnitude (Dużmańska et al., 2018). Rebenitsch and Owen (2021) demonstrate that it seems to be a linear function between duration and cybersickness subjective symptoms. It worth noting that those symptoms can remain for a variable time, depending on the software. For example, after a roller-coaster simulation, symptoms are still declared by users more than three hours after exposure (Gavgani et al., 2017). Standing rather than sitting increases the chances to provoke cybersickness (Merhi et al., 2007), as mentioned by Rebenitsch and

Owen (2021). Therefore, for work purposes, defining whether users should use INFINITY sitting or not is necessary.

Even though those side effects have been known since the beginning of VR, impacts on cognition and long-term effects are yet to be documented. However, physiological changes that correlate to subjective reports (questionnaires like the SSQ) have been documented by Gallagher and Ferrè (2018): see Table 7. According to them, cybersickness is influenced by physiological variables that can be measured with ECG (Electrocardiography, heart), EDA (Electrodermal activity, skin), or EEG (Electro encephalography, brain) (see section 3.4.2 page - 69 -). Blinks increase with time exposure and cybersickness (Lopes et al., 2020a). Therefore, we can also add to Gallagher and Ferrè (2018) list the incidences on the visual system.

Table 7: Symptoms of cybersickness associated with physiological changes according to Gallagher and Ferrè (2018)

Subjective cybersickness symptoms categories (SSQ)			Physiological changes in cybersickness	
Nausea	Oculomotor	Disorientation	Increases in	Decreases in
Discomfort	Discomfort	Difficulty focusing	Heart rate	Photoplethysmogram
Increased salivation	Fatigue	Nausea	Respiration rate	Skin temperature
Sweating	Headache	Fullness of head	Skin conductance	Heart period
Nausea	Eyestrain	Blurred vision	Gastric activity Blinks	EEG Theta power
Difficulty concentrating	Difficulty concentrating	Vertigo	EEG Alpha power	
Stomach awareness	Difficulty concentrating		EEG Beta power	
Burping	Blurred vision		EEG Gamma power	

During and after VR exposure, users report symptoms that can be correlated with physiological changes. Rebenitsch and Owen's (2021) list of factors influencing cybersickness go beyond motion sickness symptoms and vection issues. However, cybersickness is mainly explained by a visually induced motion. Therefore, cybersickness tends to overlap with other potential VR side effects. Current knowledge of cybersickness incline to human adaptation, or desensitization, to sensorimotor conflicts (Gavgani et al., 2017; Stanney, Lawson, et al., 2020). It means that repeated exposure might lead to reducing cybersickness symptoms. However, this implies maladaptation to the real world (Gallagher & Ferrè, 2018).

3.2.1.3 CYBERSICKNESS AND WORKING IN VR

Most experimental works regarding cybersickness are using video games (rollercoasters), driving tasks, or dedicated walking around (a virtual environment) tasks. Those paradigms induce cybersickness symptoms with some confidence to measure variations attributable to it. However, even if previous works provide precious information, we narrowed literature presented to work-related tasks to match the INFINITY platform's aims. The locomotion and visual feedback of this locomotion are two crucial factors leading to cybersickness. In a collaborative car design environment, Coburn et al. (2020) experimented with four moving methods: Teleport, Fade, Fly, and Manual (translation and rotation are automatic to place users in a predetermined location). After moving, participants must locate a particular part of the car. Flying proves to be the best solution for spatial location. But it implies a potential higher discomfort (cybersickness). Teleporting is the worst because of disorientation. Coburn et al. (2020) advocate for multiple choices of transition styles (locomotion) for users.

Since INFINITY consists of sharing graphs and other media in a collaborative environment, we can choose the preferred locomotion style. Since part of the work consists of data analysis and graph visualizations, we can hypothesize that users in INFINITY will be sitting (Zielasko et al., 2017). Zielasko et al. (2019) have participants moving by leaning (forward and backward) to move. Participants must find the shortest path between a pair of red vertices hidden in a node-link visualization. Since participants are sitting in front of a desk, Zielasko et al. (2019) tested two conditions: a virtual desk visually stably represented in VR and without a virtual desk. Authors do not find differences in cybersickness, task performance, and presence which open to displaying keyboard and other interfaces instead of a virtual desk. But locomotion type when analysing data also seems to be impacted by expertise in data analysis, spatial orientation ability, and video games (Lages & Bowman, 2018). When comparing real desk tasks to a virtual reality desk, some works show no difference in cybersickness symptoms (J. Guo et al., 2019). Boges et al.'s (2020) work (editing and exploring medial axis representations of nanometric scale neural structures) shows that users have to take several breaks because of cybersickness after being immersed for fifteen minutes. But side effects are not always assessed, for instance in works about data visualization in VR, e.g. (Andersen et al., 2019)

In INFINITY, visually induced motion sickness could be less of a problem since fewer tasks or stimuli are probable to imply continuous locomotion than virtual environments consisting of driving or rollercoaster games. Filho et al. with "VirtualDesk" (data visualization and analytics) show low cybersickness in different experiments (Filho et al., 2018, 2019, 2020). Previous works relating to data visualization and office work in VR showed that cybersickness needs further investigation and should be seen as a risk of side effects even in this configuration.

Forty factors can influence cybersickness occurrence in VR (Rebenitsch & Owen, 2021). Cybersickness is still a research question that requires scientific work to understand it better and to measure it. As an RIA project, INFINITY aims at making LEAs working in VR. Therefore, INFINITY should tackle part of those issues as the workplace context of VR cybersickness is little investigated in previous contributions. Based on the latest reviews and systematic reviews (Descheneaux et al., 2020; Kemeny et al., 2020; Koohestani et al., 2019; Saredakis et al., 2020; Stanney, Lawson, et al., 2020), we can infer that contributions regarding cybersickness concentrate on the visual-vestibular-proprioceptive conflicts (like motion sickness) issue but rarely visual fatigue, i.e., vergence-accommodation conflict (E. Chang et al., 2020; Fuchs, 2017; Souchet, 2020). Cybersickness seems to increase brain activity related to balance and vestibular inputs. Since visual fatigue (or oculomotor symptoms in cybersickness-related works) is pointed out as one of the main symptoms in VR side effects, it seems legitimate to focus on it (E. Chang et al., 2020). Our current focus choice does line up with Staney, Lawson, et al. (2020) agenda as we contribute to evaluation and applications researches to tackle cybersickness issues. As shown in this section, oculomotor symptoms are mainly induced by visual motion in VR. But visual fatigue should be considered not only as symptoms related to cybersickness. Therefore, the next section addresses the topic of visual fatigue.

3.2.2 VISUAL FATIGUE

3.2.2.1 VISUAL FATIGUE OVERVIEW

According to Evans (2007), visual fatigue (also named asthenopia, eyestrain, visual strain, ocular symptoms, depending on the discipline tackling this issue) generally corresponds to eye fatigue and headaches. Sheppard and Wollfsohn (2018) quote the list of symptoms by the *American Optometric Association*: eyestrain, headaches, blurred vision, dry eyes, and pain in the neck and shoulders. The subjective appreciation of these symptoms is visual discomfort (M. Lambooij et al., 2009; M. T. M. Lambooij et al., 2007). Visual fatigue is due to a weakness of the eyes or vision, i.e., resulting from a visual or ocular abnormality rather than purely extrinsic (environmental) factors. Lambooij et IJsselsteijn (2009) define visual fatigue as a "*physiological strain or stress resulting from excessive exertion of the visual system*." The generalization of the various screen usages induces this excessive exertion. Sheppard and Wollfsohn (2018) have reviewed the visual fatigue phenomenon linked to digital uses. They have determined that a large part of the population is at risk. However, they did not evaluate Augmented or Virtual Reality devices nor other devices able to display stereoscopy.

HMDs are absent of most visual fatigue reviews like the one by Coles-Brennan et al. (2019). Like screen uses, HMDs imply that users are very close to the physical screen. But with the use of lenses, they are also projected screens to stimulate user's visual system (see Figure 18 page - 44 -) (Watson & Hodges, 1995). One of the main issues regarding visual fatigue is that HMDs are displaying stereoscopic images to reproduce stereopsis mechanisms: depth cues from the environment inferred from the distance between (interpupillary-distance) our two eyes fused by our brain (Hodges & Davis, 1993, 1993, 1993; Holliman et al., 2011; A. J. Parker, 2016; L. Parker, 1983; Reichelt et al., 2010; Rößing, 2016; Souchet, 2020; Urey et al., 2011).

Depending on parallaxes applied to the two different images (one by screen in the HMD), an object can be perceived (Wann et al., 1995):

- "in front" of the virtual screen with negative parallax
- "behind" the virtual screen with positive parallax
- "on" the virtual screen with null parallax

Terzić and Hansard (2017) conduct a review on causes of visual discomfort, which points to future problems with HMDs since they display stereoscopy. Displaying stereoscopy is known to induce visual strain in general (Fortuin et al., 2010; Karajeh et al., 2014; D. Kim et al., 2011; Kuze & Ukai, 2008; M. Lambooij et al., 2009; M. T. M. Lambooij et al., 2007; Sasaki et al., 2015; Sugita et al., 2014).

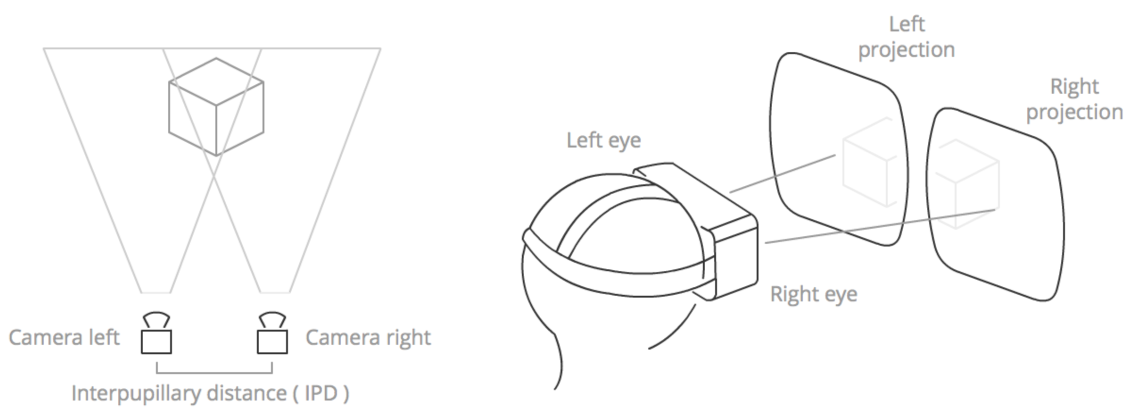


Figure 18: Principles of generating a stereoscopic image for HMD (left) and display (virtual screen), in projection form, in HMD (right), (ariellalehrer, s.d.)©

Ukai and Howarth (2008) conclude their review on visual fatigue caused by moving stereoscopic images by stating that the theory applying to visual fatigue provoked by vergence-accommodation conflict remains unclear. In VR, cybersickness' "evolutionary theory" provides predictions about vergence-accommodation conflict (Stanney, Lawson, et al., 2020). However, as introduced in section 3.2.1 page - 39 -, the theory widely accepted is the sensory conflict theory. Fuchs (2017) indirectly proposes the sensorimotor contingencies theory by discussing sensorimotor conflict when describing the vergence-accommodation conflict. In line with Fuchs, several late contributions that give an overview about cybersickness and VR side effects also use the concept of sensorimotor systems (Stanney et al., 2020; Weech et al., 2018). O'Regan and Noë (2001) developed the Sensorimotor Contingencies Theory. The sensorimotor conflicts concept relies on this theory which states that computations do not fully constitute perception in the brain (inner representational models). The perceiver is an active agent engaging with the world. Therefore, perception is intimately linked to motor actions (sensorimotor contingencies) (Bishop & Martin, 2014; Buhrmann et al., 2013; Dell'Anna & Paternoster, 2013). Hence according to this theory, "*sensory experience is not generated by activating an internal representation of the outside world through sensory signals, but corresponds to a mode of exploration and hence is an active process*" (Maye & Engel, 2013). According to Vázquez (Clavel Vázquez, 2020), predictive processing/coding completes the Sensorimotor Contingencies Theory predictions despite discordant representations and explanatory strategies. Predictive processing states that *"perceptual content emerges from probabilistic inference on the external causes of sensory signals*" (Seth, 2014). The concepts of predictive coding and sensorimotor contingencies theory are in debate in cognition (Flament-Fultot, 2016; Marvan & Havlík, 2021; Vernazzani, 2019; D. Williams, 2020). Finally, Bando et al. (2012) evoke the complexity of what causes visual fatigue in VR. Visually induced motion sickness and vergence-accommodation conflict play a role. Both visually induced motion sickness (in which we talk about oculomotor symptoms) and vergence-accommodation conflict could trigger visual fatigue. Because the theoretical background of cybersickness is still debated, it is hard to be sure on how to treat visual fatigue regarding general predictions on VR side effects. Several previous works about cybersickness talk about vergence-accommodation conflict (E. Chang et al., 2020; Descheneaux et al., 2020; Nesbitt & Nalivaiko, 2018; Rebenitsch & Owen, 2021). But it remains unclear if they link it to sensory conflict theory or sensorimotor contingencies theory.

Despite all those excessive exertions of the visual system when using HMDs, they don't seem to provoke myopia after 40 minutes of exposure (Turnbull & Phillips, 2017). However, HMD use can contribute to factors that affect myopia, and the impact on accommodation and vergence functions also could be a long-time concern (Németh et al., 2021). Therefore, we will concentrate on visual fatigue rather than another issue that could arise with user's eyes since we are concerned with what happened while VR is used.

3.2.2.2 VISUAL FATIGUE OCCURRENCE

Stereoscopy allows us to reproduce binocular and proprioceptive (or oculomotor) depth cues. Stereoscopy aims to provide clear stimuli for our eyes in HMDs (Rotter, 2017). Binocular cues mean they can only be seen with two eyes (Blake & Wilson, 2011). Due to their horizontal distance, the inter-pupillary distance of human eyes, each eye captures two slightly different images of the same fixation point. The inter-pupillary distance is on average 65 mm (ANSES, 2014), ranging from about 50 to 77 mm for the general population (M. Lambooij et al., 2009; Stanney, Lawson, et al., 2020). But this may vary depending on the country and can be wider if children are included (Dodgson, 2004). The disparity between the image of each eye that is fused by our brain via stereopsis gives relative depth information (see Figure 18 page - 44 -): a depth map (Landy et al., 1995).

Two proprioceptive depth cues provided by stereoscopy are vergence and accommodation (Fuchs, 2017; M. Lambooij et al., 2009; Neveu et al., 2016). Vergence is the mechanism allowing our eyes to move in their orbit to fix the same point (Searle & Rowe, 2016; Millodot, 2017). An image of the objects centred on each retina is thus obtained. The optical axes are oriented towards the viewed object (see Figure 19 page - 46 - "Vergence"). The outer muscles apply the movement. The vergence comprises four distinct movements, of which the convergence and the reverse movement: the divergence (Howard & Rogers, 1996). This particular movement co-occurs for both eyes.

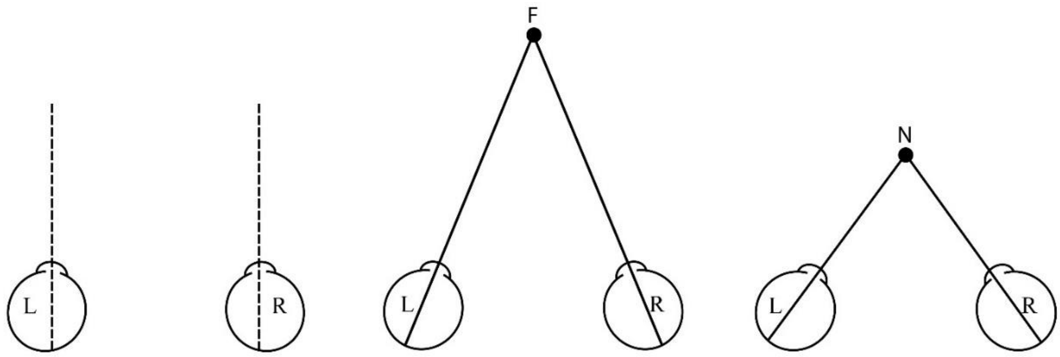


Figure 19: Vergence mechanism, different movements to align the optical axes according to the distance from the viewed object (F means Far, N means Near object) from left to right: vergence to an infinite object, vergence to a far object, and vergence to a near object based on (Souchet, 2020)

Accommodation is the mechanism, an involuntary reflex, allowing a clear view of a fixed object (Millodot, 2017). If a nearby object is fixed, the ciliary muscles contract (Glasser, 2006) and distort the lens, i.e., its curvature, thus allowing the light reflected by an object to be refracted clearly on the fovea (Burd et al., 1999: see Figure 20 page - 47 -). This results in a change in the dioptric power of each eye (clearer sight).

Disparity and blur drive the vergence and accommodation mechanisms (Sweeney et al., 2014). According to Schor and his colleagues' model (Schor, 1992; Schor & Kotulak, 1986; Schor & Tsuetaki, 1987), vergence and accommodation are two dual parallel feedback control systems that interact via cross-links. As summarized by Lambooij et al. (2009): "*accommodation and vergence interact to provide comfortable and clear, binocular, single vision [under natural viewing].*"

However, stereopsis is only possible for a limited number of positions in space. The brain will only consider the point of vergence as unique despite the binocular disparity if the distance meets certain conditions. This set of merging points can be represented by the human's binocular horizontal field of view of 120°. The Horopter, also called the Vieth-Müller Circle, was defined mathematically by Vieth and Müller. It corresponds to a set of locations on a baseline in space from which the relative depth is judged. On that baseline, fusion without diplopia (double vision) is possible (R. E. Patterson, 2015). Retinal disparity on the horopter is about 0°. Panum's fusion area defines the area around the horopter in which clear and single vision (without diplopy) is still possible with two images with disparity (Mitchell, 1966). Fusion is possible without too much strain on the visual system on Percival's area (M. Lambooij et al., 2009: see Figure 21 page - 47 -). Shibata et al. (2011) assuming that the maximum and minimum relative distance of the comfort zone is between 0.8D (1.28m) and 0.3D (3.33m).

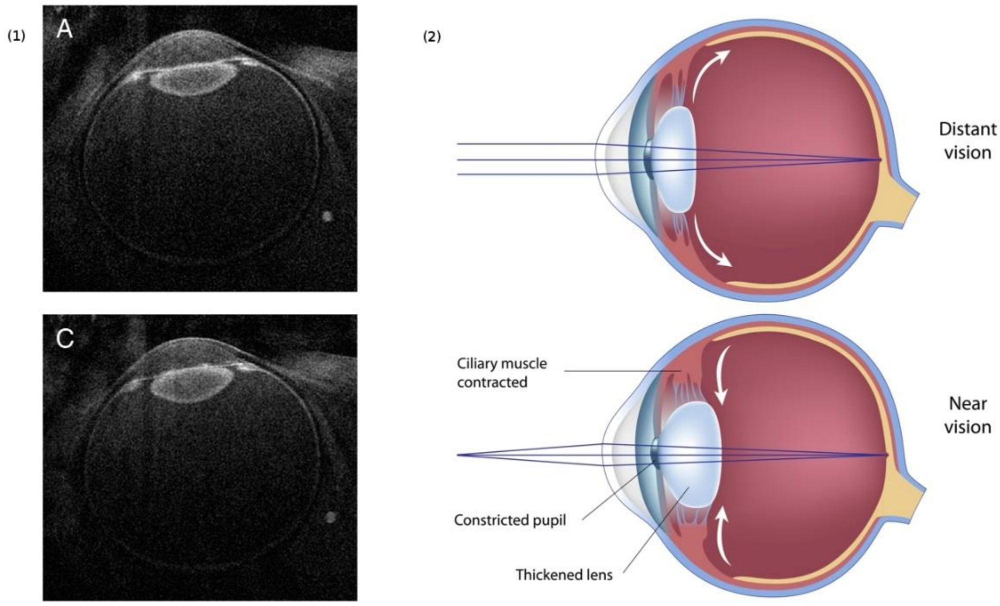


Figure 20: Accommodation mechanism, distant object and near object (1) Based on Kasthurirangan et al. (2011), Eye MRI in A - accommodation on a distant object, in C - on a near object with a 27-year-old subject. (2) Diagram illustrating the mechanism, (charllaas, s.d.)©

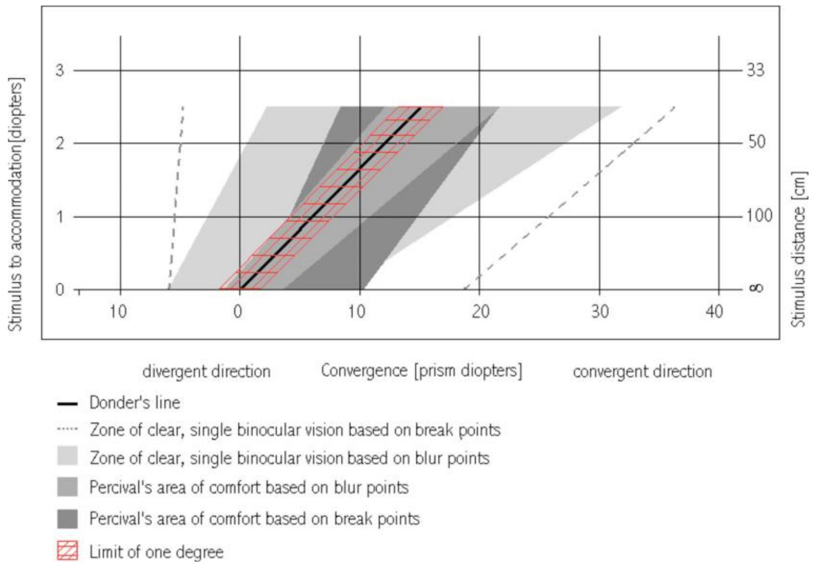


Figure 21: Synthesis of different viewing zones for comfortable viewing by Lambooij et al. (2009): "the zone of clear, single binocular vision, two different areas of comfort defined by Percival's criterion, one based on blur points and one based on breakpoints and the zone formed by the 1° limit. The black solid line depicts Donder's line."

Stereoscopy sometimes requires fusion outside of the comfort zone (Fortuin et al., 2010; M. Lambooij et al., 2009). When it occurs, the habitual crosslink between accommodation and vergence is mismatched because accommodation applies on screens plan while convergence applies to objects of interest (Banks et al., 2013; Emoto et al., 2005; Fuchs, 2017; J. Kim et al., 2014; Leroy, 2016: see Figure 22 page - 48 -). Several scientific works treat in detail accommodation and vergence mechanisms and conflicts due to stereoscopy (Banks et al., 2012, 2013; Fuchs, 2017; Hoffman et al., 2008; B. Jiang et al., 2002; J. Kim et al., 2014; M. Lambooij et al., 2009; Leroy, 2016; Mays, 2009; Neveu et al., 2016; Rößing, 2016; Schor, 1992).

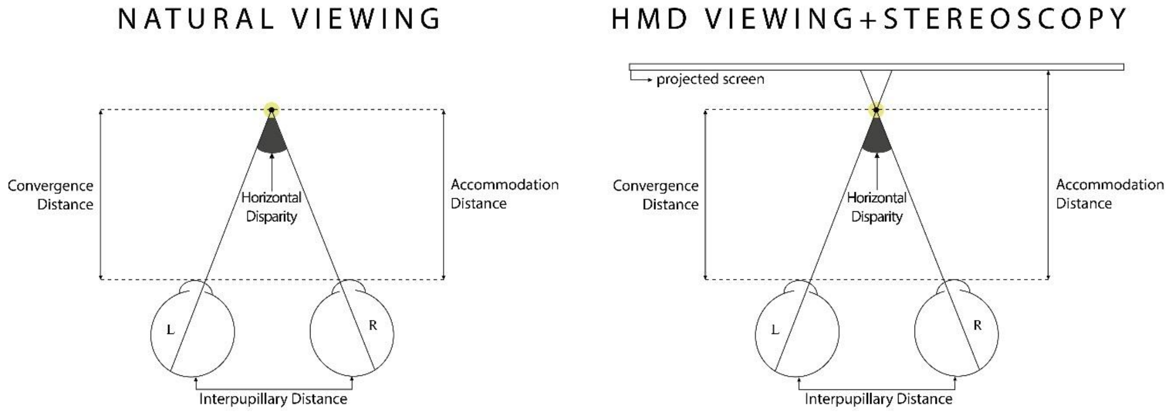


Figure 22: Comparison of natural binocular viewing and HMD viewing with stereoscopy (near object, negative parallaxes in this example): accommodation and convergence occur on the same plane in natural viewing but in HMD viewing with stereoscopy, there is a mismatch between accommodation and vergence that are crosslinked mechanisms.

Stereoscopy induces the vergence-accommodation conflict (Bando et al., 2012; Ukai & Howarth, 2008) in HMDs (Matsuura, 2019; Yuan et al., 2018). There is no theoretical consensus to rely on. But this conflict is a concern for VR everyday uses (A. T. Biggs et al., 2018). This sensorimotor conflict is the main explanation of visual fatigue with HMDs (Fuchs, 2017). Studies with the older generation of HMDs measured visual fatigue due to vergence-accommodation conflict (Mon-Williams et al., 1993; Mon-Williams & Wann, 1998; Rushton et al., 1994). A new generation of HMDs still causes visual fatigue (Souchet et al., 2018; Hirota et al., 2019; Souchet et al., 2019; Y. Wang et al., 2019; Yoon et al., 2020) and visual discomfort (Bracq et al., 2019; Cho et al., 2017). Vergence-accommodation conflict while displaying stereoscopy still provokes visual fatigue in HMDs. A lack of contributions to document that affect, outside of knowing it still exists with HMDs, has been pointed out (Szpak et al., 2019). But other factors, uncomfortable fusion and vergence-accommodation conflict can also play a part in visual fatigue (Jie Guo et al., 2017; Hoffman et al., 2008; Yano et al., 2002, 2004), Table 10 page - 52 -.

Table 8: Possible factors inducing visual fatigue in VR.

Demographics	Hardware	Software
Age	Vergence-accommodation conflict	Duration of display use
Stereoscopic visual ability (stereo-blindness)	Optical misalignment (between HMD lenses and eyes)	Binocular disparity (possible and comfortable fusion)
	Geometrical distortion	Motion parallax
	Luminance	Texture gradients
	Blue light	Occlusion
		Blur
		Colors

Visual fatigue seems time-related: the more prolonged VR exposure, the higher the visual fatigue. Guo et al. (2019) find that symptoms are increasingly severe and that severity increases faster during the first 20 minutes. Guo et al. (2020) tested the exposure of almost eight hours to VR and reported that it increasingly impacts accommodative response and pupil size. But it is comparable to impacts in VR and 2D screen working tasks (text error corrections) for pupil size.

Part of the population is "stereo-blind." These individuals are missing or have immeasurable binocular depth perception. The proportion of concerned individuals varies according to tested populations and measurement conditions from 2.2% to 32% (Bosten et al., 2015; Hess et al., 2015; M. Lambooij et al., 2009). Moreover, although not necessarily impacting the discriminating abilities of the depth of objects, the precision abilities of stereopsis diminish with the age of humans (Schubert et al., 2016). It also seems that poor stereo acuity drives higher visual fatigue (Ramadan & Alhaag, 2018). Therefore, this population seems to present higher risks of visual fatigue.

Blue light might also contribute to visual fatigue, but it remains unclear how this is a significant factor or not since little research has been conducted and not superficially with HMDs (Heo et al., 2017; Lawrenson et al., 2017; Priya & Subramaniyam, 2020; Tu et al., 2021). Continuous (chronic) exposure to blue light might be damaging to the retina (S. F. Ahmed et al., 2018). Since HMDs are using OLED and LCD technologies, we can picture that blue light could be a factor of visual fatigue when using VR. As shown in previous contributions regarding stereoscopy and near work, blue light implies less accommodation (Panke et al., 2019). The lighter the displayed stimuli, the higher visual fatigue (Erickson et al., 2020; A. Wang et al., 2010). The more frequent colour changes, the higher visual fatigue (J.-Y. Kim et al., 2016). The more dynamism in videos, the more visual fatigue (Kweon et al., 2018). A report from Anses, the French Agency for Food, Environmental and Occupational Health & Safety about lights effects on health includes blue lights (range from 400 to 490 nm) and indicates that the "phototoxicity" range (450 to 470 nm – deep blue) has possible effects (ANSES, 2019): 1) on myopia (positive or negative), and 2) on dry eye syndrome. This concerns screens. Blue light seems to facilitate visual discomfort in general (not restricted to screen use). However, according to the report, proofs of effects on humans are limited, even with the contribution of blue light, but long-term issues include (ANSES, 2019): 1) 480 to 490 nm: disturbance of circadian rhythms, disturbance of sleep if exposed to blue light during the evening, at night before sleep or even during the day (Wahl et al., 2019), and 2) phototoxicity (Youssef et al., 2011) on the cornea (Mehra & Galor, 2020; Niwano et al., 2019). To this date, directive 2006/25/EC (artificial optical radiation) of the European parliament and council applies.

Factors inducing visual fatigue and cybersickness are sometimes similar (see Table 6 page - 40 - and Table 8 page - 48 -). This similarity does not help to clarify what is the domain of visual fatigue and what is the domain of cybersickness. Cybersickness is about visual-vestibular-proprioceptive conflicts, while visual fatigue might lean on more minor vestibular-based conflicts. In both cases, oculomotor performance seems negatively impacted in VR (Valori et al., 2020). However, we can see that similar factors are to be considered both in cybersickness and visual fatigue. In the next section, we concentrate on works tackling visual fatigue when working in VR. However, visual fatigue and visually induced motion sickness seem to be different (Y. Wang et al., 2019).

3.2.2.3 VISUAL FATIGUE AND WORKING IN VR

Visual fatigue already represents a risk for a large part of the population, at least 50%, who use various screens (Sheppard & Wolffsohn, 2018). Working at short distance from computer screens causes dry eye, ametropia, and impairs accommodation or vergence mechanisms. Therefore, the addition of HMDs would increase screen use at work for LEAs workers and specifically analysts whose work requires extensive computer use (Silva et al., 2019). HMDs seem to drive higher visual fatigue than PC, tablet or smartphone uses (Han et al., 2017; Souchet et al., 2018; X. Yu et al., 2018; Y. Zhang et al., 2020). Here, we focus on visual fatigue while using VR and right after.

Examples of video game use show that VR impacts accommodation and convergence, whether use duration is 10 or 50 minutes (Ancret Szpak et al., 2020). In a study by Szpak et al. (2020), it took 40 minutes after VR use for those effects to disappear. However, their study shows that less than 10 minutes did not impact the user's visual system while the duration of 10- and 50-minutes exposure did not change oculomotor functions differently.

Several works present comparable results about accommodation and vergence negatively impacted after playing video games (Alhassan et al., 2021; Yoon et al., 2020). However, studies sometimes find contradictory results: no decrease in accommodative and vergence functions after 25 minutes at playing like Munsamy et al. (2020), improvement of the amplitude of accommodation after 10 minutes of use two times a day for two weeks (Long et al., 2020) and similar findings (Mohamed Elias et al., 2019). According to INFINITY scenarios, video games in VR findings might not apply to typical tasks of police workers in a VR environment. Nine studies of which interaction types could relate to what the INFINITY platform would require from users, detect visual fatigue: see Table 9 page - 50 -.

Table 9: Visual fatigue detected consequently to HMD use depending on tasks that are comparable to work in INFINITY (video games that require interactions or stimuli too far from tasks an analyst might encounter in VR have been excluded).

Reference	Task	Effects on visual system	Duration (min.)	HMD
(Souchet et al., 2018)	Reading and Responding with box selection through head movement, learning job interview (VR versus PC)	Higher visual fatigue with VR than PC screen. Equivalent visual fatigue with VR between 2D and S3D for low disparity and not spatial-dependent tasks VR negatively impacts punctum proximum of accommodation, stereoscopic acuity, ease of accommodation	30	Samsung Gear VR + S6
(Jacobs et al., 2019)	Visual search task of objects at various depths	Dynamic adjustment led to higher blink rate and smaller pupil diameter = visual fatigue	20	HTC Vive Pro
(Julie Iskander et al., 2019)	Following cubes at various depths	Vergence angle and eye-gaze performance negatively impacted VR. Vergence angles have higher variability in VR than in natural viewing = visual fatigue and misperception of depth	3	HTC Vive
(Shen et al., 2019)	Watching 2D videos	blink radio in the constant speed disparity changes group is higher	60	HTC Vive
(Souchet et al., 2019)	Reading and Responding with box selection through head movement, learning job interview (VR versus PC)	Punctum proximum of accommodation negatively impacted Visual acuity negatively impacted Cyclical stereoscopy is worse than continuous stereoscopy	30	Samsung Gear VR + S6
(Y. Wang et al., 2019)	Watching video	increasing fixation features and blinking over time binocular crossed cylinder test, negative and positive relative accommodation, left and right pupil diameter, left and right lens thickness impacted	3	HTC Vive
(Hirota et al., 2019)	Block game and Video	Binocular fusion maintenance lower after task similarly between VR and PC screen	30	PlayStation VR

(Yoon et al., 2020)	Playing Minecraft (gathering block resources and building structures)	near point of accommodation and convergence as well as increased accommodative lag after VR use	30	Oculus Rift
(Thai et al., 2020)	Watching video and eye-relaxation exercises	Blinks decrease in VR	30	HTC Vive Pro

Despite minor works directly tackling VR-induced visual fatigue at work, existing experiments point that visual fatigue arises with similar interactions and contents to what working in VR would require. While performing cybercrime-related tasks in VR, non-expert users rated visual fatigue as the highest side effect (subjective) in Kabil et al. (2020) study. In INFINITY, one typical task is to work at producing graphs and perform visual analysis. Volume visualization does not always require stereoscopic images (Laha et al., 2012). By extension, not all tasks within INFINITY would require stereoscopy. Therefore, stereoscopy use must be used sparingly as it provokes visual fatigue.

Since little work directly investigates visual fatigue in the context of INFINITY tasks, dedicated works within the project should concentrate on better measuring, detection, and evaluation of its consequences on human performances while working in VR. As shown in this section, visual fatigue is already a concern for general screen uses. VR would be an extra load on worker's visual system, therefore their well-being. Furthermore, possible influence on available memory workload could directly influence work performance while using VR (see section 3.5.1.3 page - 85 -).

3.2.3 MUSCLE FATIGUE AND MUSCULOSKELETAL DISCOMFORT

3.2.3.1 MUSCLE FATIGUE MUSCULOSKELETAL DISCOMFORT OVERVIEW

According to Gandevia (2001), muscle fatigue defines an "*exercise-induced reduction in the ability of a muscle or muscle group to generate maximal force or power.*" It leads to difficulty performing a voluntary task (Gruet et al., 2013; Taylor et al., 2016). Muscle fatigue mainly treats intense exercises like sport or physically demanding works (Wan et al., 2017) (e.g., prolonged standing (Coenen et al., 2018; Halim et al., 2012)) but also screen work (Coenen et al., 2019). According to them, repeated issues regarding muscle load can lead to Musculoskeletal disorders and are the most common (almost 24% of EU workers) work-related problem in Europe (European Agency for Safety and Health at Work, 2007). For office workers, neck, shoulder, forearm/hands pain, upper and low back pain are the primary disorders associated with office work (Calik et al., 2020; Eltayeb et al., 2009; Frutiger & Borotkanics, 2021; Heidarimoghadam et al., 2020). Sitting for computer work is associated with short-term adverse effects such as physical discomfort (Baker et al., 2018). It's worth noting that a Police work shift pattern is normally 12 hours so sitting in one position for a long period of time is quite likely. But it doesn't relate to VR use. Despite some short-term physical discomfort, musculoskeletal disorders appear at a chronic temporality. After a few minutes of rest, users recover from muscle fatigue (Sesboüé & Guincestre, 2006). However, symptoms associated with prolonged use of computers and the internet are headache, neck and wrist pain, and backache (Borhany et al., 2018). Such symptoms are likely to arise in VR as well. Alike visual fatigue, computer, and office work already raises the issue of musculoskeletal discomfort, and VR could add to physical load (Reenen et al., 2008; Waongenngarm et al., 2020).

3.2.3.2 MUSCLE FATIGUE OCCURRENCE MUSCULOSKELETAL DISCOMFORT

In virtual reality, users interact with a computer-generated virtual environment. The stimuli, inputs from users, and feedbacks depend primarily on HMDs. Then, depending on the interaction modalities, a user can use controllers or their hands to induce changes in this virtual environment. Ultimately, the entirety of the body could be interfaced. Therefore, users need to wear different hardware and perform repeated gestures that are not always in their usual habits and can lead to muscle fatigue. Users might need to force their upper limbs to stay in sight of tracers, leading to discomfort and fatigue. Since physical load varies heavily depending on the work context, we directly focus on VR-related factors. In Table 10 page - 52 -. We summarized factors identified in 11 contributions regarding muscle fatigue and musculoskeletal discomfort while using VR (Bourdin et al., 2019; Chihara & Seo, 2018; Dube & Arif, 2019; Kartick et al., 2020; E. Kim & Shin, 2018; D. H. Lee & Han, 2018; G. Li et al., 2020; M. Li et al., 2020; Penumudi et al., 2020; Y. Song et al., 2019; Yan et al., 2019).

Table 10: Possible factors inducing muscle fatigue and musculoskeletal discomfort in VR

Demographic	Hardware	Software
Age	Weight	Duration of immersion
Body mass index	Belts (attaching HMD to head)	Object angle location
	Interaction devices	Gesture amplitude
	Position tracking error	Tasks repetition
	HMD Resolution	Head rotations required
		Body rotations required
		Sitting or standing
		Body parts representation and feedback (avatar)

Contributions used to define factors influencing muscle fatigue and musculoskeletal discomfort are presented in the following section as they apply to possible tasks while working in VR.

3.2.3.3 MUSCLE FATIGUE, MUSCULOSKELETAL DISCOMFORT, AND WORKING IN VR

During the late 90s, Nichols (1999) had already identified issues regarding muscle fatigue or musculoskeletal discomfort. E. Kim and Shin (2018) compare keyboard and mouse document editing tasks on a computer and an HTC Vive. The authors show that HMD causes higher physical stress because of the weight and resolution (reading text). VR text-entry requires more contributions regarding muscle fatigue (Dube & Arif, 2019). The weight of HMDs themselves could be a source of discomfort (Yan et al., 2019) as the user's neck joint torque is affected and the optimal center of mass position of HMDs is varying depending on a user's posture (Chihara & Seo, 2018; Ito et al., 2019; Sun et al., 2019). Depending on the number of belts, this physical stress on the neck because of the HMD weight can be perceived as higher by users, the lower the number of belts (Y. Song et al., 2019). According to Penumudi et al. (2020), shoulder flexion angle, neck flexion moment, muscle activities of the neck and shoulder, and excessive vertical target locations when interacting with targets at several angles in the 3D environment are likely to drive to musculoskeletal discomfort. Interaction gestures play a role depending on their amplitude. It can lead to higher musculoskeletal discomfort, so some contributions develop micro gestures (G. Li et al., 2020). However, depending on the tasks in the virtual environment, stronger involving ofthe body can be necessary (Kartick et al., 2020). When comparing the same real gestures versus VR gestures (CAVE), Ahmed et al. (2017) show that physical fatigue is higher in VR. Bourdin et al. (2019) showed that modifying postural/gesture feedbacks of a user's avatar in VR unconsciously drive motor and muscular adjustments. Time seems a factor to consider as watching videos in VR provokes musculoskeletal modifications (D. H. Lee & Han, 2018). But watching 360° videos despite more neck movements seems to lead to less fatigue than traditional video (ibid.). As little as 15 minutes in VR for laparoscopic tasks drive users to declare slight physical discomfort (M. Li et al., 2020).

Few contributions have investigated possible muscle fatigue that is caused by interacting with today's virtual environments and HMDs. Based on such little previous scientific work, it is difficult to identify the magnitude of possible risks regarding this issue. But like any human-computer interaction situation, VR could ultimately lead to repetitive strain injury (van Tulder et al., 2007). Therefore, INFINITY partners need to acknowledge muscle fatigue could influence platform use and user's discomfort feeling. However, since VR requires interactions different from computer work, it could also be a way to induce task variation at the job level, which might help alleviate general musculoskeletal discomfort and, ultimately, disorders (Luger et al., 2014).

3.2.4 SUMMARY OF VR SIDE EFFECTS RISKS

Most paradigms to study Cybersickness are games or videos inducing a lot of vection to make sure that symptoms will occur (rollercoaster, multiple head movements, walking in VR…). However, those paradigms little represent the work experienced by a data analysis and investigation team. Minor contributions regarding visual fatigue and the vergence-accommodation conflict in VR are available to date in a working context. But what arises from our review is that cybersickness, visual fatigue, and physical fatigue are a concern as those side effects consequent to VR use could deteriorate the user's wellbeing at work. Ultimately, generalizing VR when part of the population is at risk of side effects could, in the future, become discriminatory for potential workers (Stanney et al., 2020). Many different factors induce the severity of side effects symptoms. One is the duration of exposure. Therefore, work in VR on the INFINITY platform should be weighted and dedicated to a limited number of tasks. Even if habituation to VR, which seems to reduce side effects, has been documented, medium to long-term effects is still unknown. Very little experimental data correspond to a work environment. During experiments with VR, more than 15% of participants are susceptible to drop out because of VR side effects (Saredakis et al., 2020). For INFINITY, this implies that part of the workers might not even maintain platform use.

T2.2 of INFINITY calls for guidelines to ensure the user's wellbeing. The existing literature draws guidelines. However, it should be clear to potential VR users that no existing method can fully alleviate VR side effects. Therefore, members of the INFINITY project should contribute to ongoing scientific work regarding VR side effects. The EU-OSHA already identified these issues (*Digitalisation and Occupational Safety and Health*, 2019). Therefore, we can reasonably imagine that regulation and legislation regarding VR use at work shall emanate from the EU. For INFINITY to anticipate future regulations, avoid non-compliance of the project with required ergonomic standards.

Based on this review of VR side effects, robust methods to monitor cybersickness, visual fatigue, and muscle fatigue require more scientific contributions. No theory predicting VR side effects makes a consensus for now, and peers require more experimental work. Therefore, INFINITY, as an RIA project, can contribute to such work in the frame of WP4 and WP7.

3.3 STRESS AND WORKING IN VR

3.3.1 INTRODUCTION

Stress is a significant issue at the workplace. It impacts workers' health and well-being (Hirschle et al., 2020; Wong et al., 2019). It can lead to depressive symptoms (Theorell et al., 2015), burnout symptoms (Aronsson et al., 2017), hypertension (M.-Y. Liu et al., 2017), or type 2 diabetes mellitus (W et al., 2021). But these are effects of chronic stress. In this section, we are interested in how acute psychological and physical stress can be induced at the workplace when using VR and how it can impair VR use performance. General, occupational stress is not tackled as it would be too much of a complex undertaking. Similarly, we do not encompass the plentiful stressors police workers, such as crime analysts (Green & Rossler, 2019; Fansher et al., 2020; Edwards et al., 2021), are exposed to (Burke, 2016; Di Nota et al., 2020; Hickman et al., 2011; Maran et al., 2015; Shane et al., 2019; Webster, 2013). The focus is on what can occur while using VR to fulfil the scenarios from INFINITY. Police workers, within the INFINITY scenario, are exposed to events that Conn (2016) defines as "Explosive": "*crimes in progress […] and terrorist situations*."

Stress at work can be approached via the challenge-hindrance stressor framework (Lepine et al., 2005; C. Liu & Li, 2018; Mazzola & Disselhorst, 2019). However, consideration of stressor types concerns the individual work experience broadly, at the job level. The focus is on the relationship between stress and performance at work on specific tasks in VR, not on the entire work experience.

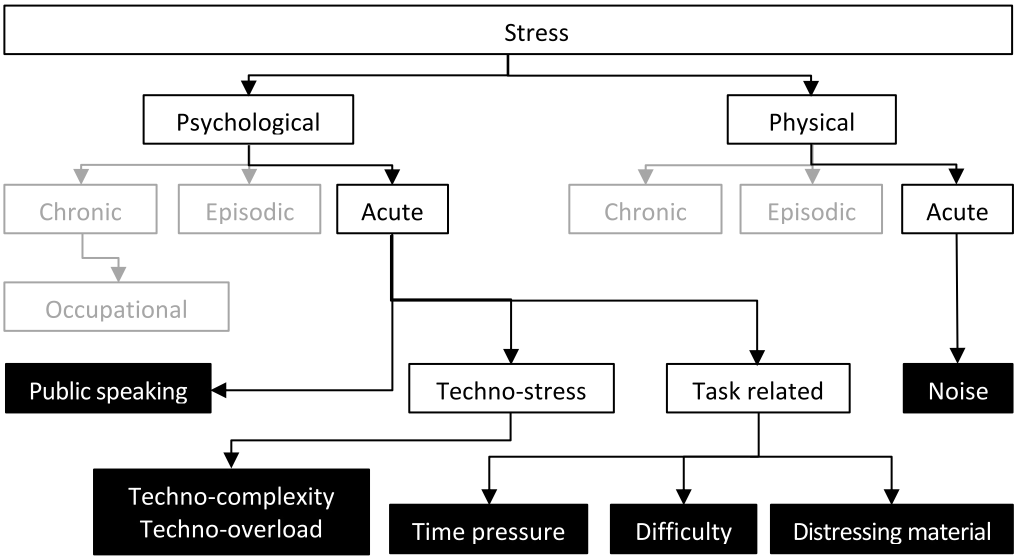


Figure 23: Stressors of interest in INFINITY are in black boxes in relation to the type of stress

First, an overview of the stress factor. Then, acute stress occurrence is described. Finally, the six stressors relevant for INFINITY are addressed. The purpose is to understand how stress can impact use efficiency (task performances) and how VR can be a stress factor for workers from LEAs. The topic is addressed by concentrating on specific aspects of stress (see Figure 23 page - 54 -).

3.3.2 STRESS OVERVIEW

Stress is a concept, and its definition is not unified in a consensual theory (Epel et al., 2018). Revisiting stress definition based on theories of the neurobiology of a "Bayesian and Selfish brain" (Peters et al., 2017) define stress as: "*the individual state of uncertainty about what needs to be done to safeguard physical, mental or social well-being.*" This definition relies on human strategy to reallocate energy to reach homeostasis or allostasis in reaction to stress induction, which defines adaptation, to maintain equilibrium in human's systems (Asarian et al., 2012; Boucher & Plusquellec, 2019; P. J. Dewe et al., 2012; Ganzel et al., 2010; Ramsay & Woods, 2014). We rely on the Transactional Theory of Stress (A. Biggs et al., 2017; Lazarus & Folkman, 1984) which predicts that stress as a process is: transactional, and the path from a stressful situation to outcome is individualized, situationally specific, and inseparable from the cognitions of the experience process. Theoretical debates on stress remain, and concurrent theories exist, such as the Generalized Unsafety Theory of Stress (Brosschot et al., 2018). Here, to disambiguate our interpretation of stress (Bienertova-Vasku et al., 2020), we consider stress as a "*negatively perceived factor or situation*" (psychology). Kim and Diamond (2002) list three components defining stress (Fink, 2016): arousal (or excitability), perceived aversiveness, and uncontrollability. According to Cohen (2011), arousal: "*refers to the tonic state of cortical activity elicited by subcortical reticular formation that results in increased wakefulness, alertness, muscle tone, and autonomic response (e.g., heart rate and* *respiration*).” According to Kim and Diamond (2002), aversiveness is: “*an indication that the subject would avoid or attenuate the intensity of the stressor if given the opportunity.*” In this context, aversive stimuli are negative stimuli (events). Uncontrollability defines adverse events that an individual cannot control (Breier et al., 1987).

We purposely summarized, approximately, the complex (Yaribeygi et al., 2017; Godoy et al., 2018; Ebmeier & Zsoldos, 2019; Tsigos et al., 2020) human stress response by only listing where (neuro-anatomy) the response starts and how (bio-chemically) it induces changes that impact physiological functions. The autonomic nervous system (ANS) is often referred to as the starting point of a stress response. It adapts the organism to internal and external changes, maintaining bodily homeostasis and coordinating bodily responses (Richter & Wright, 2013a; Johnson, 2018). ANS has three subdivisions (see Figure 24 page - 56 -):

- sympathetic nervous system (SNS) (Richter & Wright, 2013c), which controls the "fight or flight" response preparing the body for physical activity, the effort to either fight off or flee from danger (Chamberlain & Meuret, 2017)
- parasympathetic nervous system (PNS) (Richter & Wright, 2013b), which controls the "rest and digest" response, restoring to counterbalance stress reaction
- enteric nervous system (ENS), which controls the “gut-brain axis” gastrointestinal function (Rao & Gershon, 2016)

These three subdivisions induce the human biological response to stress that Fink (2016) describes, which is highly specific to each individual:

1) Two stage appraisal from perception by the sensory system (E. B. Goldstein & Brockmole, 2016; Windhorst, 2009) and comparing to previous experience (cognitive appraisal) (Campbell et al., 2013). The challenge is assessed. Primary appraisal: is it a stressful challenge/a threat? Secondary appraisal: how can I confront the stressor, coping with it (A. Biggs et al., 2017; Folkman, 2013; Lazarus & Folkman, 1984)?
2) Activation of the sympathetic adrenomedullary (SAM) (J. R. Carter & Goldstein, 2014) limb that rapidly release catecholamines (D. S. Goldstein, 2010b), noradrenaline, and adrenaline (D. S. Goldstein, 2010a).
3) Simultaneous (with SAM) activation of the hypothalamic-pituitary-adrenal (HPA) (Smith & Vale, 2006).

The SAM by releasing catecholamines: increase cardiac output, increase blood pressure, shunt blood from the skin, shunt gut to skeletal muscle and trigger the release of glucose from the liver into the bloodstream. Simultaneously, the HPA axis releases adrenal glucocorticoids and cortisol (Dickerson & Kemeny, 2004; Stalder & Kirschbaum, 2018). These changes lead to emotional (Roger, 2016), behavioural (Dantzer, 2016), and cognitive (Calvo & Gutiérrez-García, 2016) modifications.

Stress defines a wide range of human interactions with its environment (Schneiderman et al., 2004). In our context, we focus on acute stress provoked by using VR to work. Our main goal is to monitor stress response during such VR use to ensure an efficient interaction. Therefore, we describe acute stress response occurrence hereinafter.

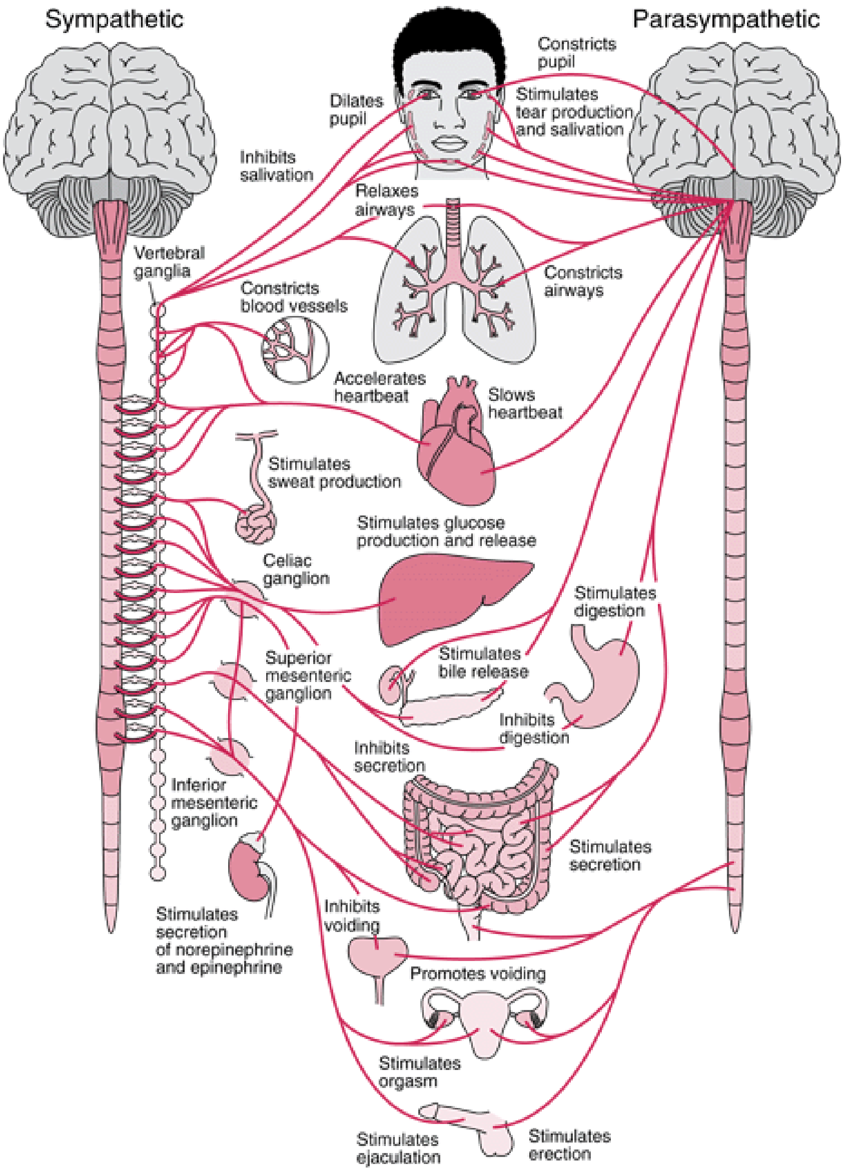


Figure 24: Low (2020) autonomic nervous system divisions (Sympathetic and Parasympathetic) and impacts on organs as well as physiology © Merck and the Merck Manuals Merck & Co., Inc., Kenilworth, NJ, USA

3.3.3 ACUTE STRESS OCCURRENCE

Acute stress defines a sudden or short time stressor (trauma, perceived threat, death of a loved one, job loss…) by opposition to chronic stress (long time stressor) (Fink, 2007, p. 192-193). Acute stress with animal models is usually divided into physical (shock, cold, loud noises…) and psychological (novelty, social conflict, unfamiliarity with environment…). The acute stress response is complex. McEwen (2007) proposes an overview of the brain's role. At the neurological level, the acute stress response is characterized by activity and connectivity (van Oort et al., 2017) in the salience network (Uddin, 2017) and increased activity in the default mode network (Alves et al., 2019). Acute stress responses occur within seconds to several hours (Godoy et al., 2018; Shields et al., 2017). At the physiological level, this response is described above based on Fink's (2016) contribution.

In our context, we are interested in both physical and psychological stress (Scott M. Monroe & Cummins, 2015; S.M. Monroe & Slavich, 2016). With animal models, the two have been differentiated according to Li et al. (2019): "*effects of physical stress appeared early but [is] relatively moderate, whereas the effects of* *psychological stress [appears] late but [is] more severe.*" However, in humans, physical and psychological stress could interact and accumulate (Abdelall et al., 2020). Stress responses are individual and depend on coping with given stressors (P. Dewe, 2017; Stephenson & DeLongis, 2020). Although we described acute stress as our primary interest, in our context, stress can also be episodic: frequently and consistently in multiple episodes.

Hereabove, stress as a general phenomenon is presented through the Transactional Theory of Stress (A. Biggs et al., 2017; Lazarus & Folkman, 1984). The theory applies to stress at the workplace (P. Dewe, 1991). It has declined to predict acute stress processes by humans. Stress at the workplace covers various experiences one can face (Colligan MSW & Higgins, 2006). In our context, workers are supposed to conduct analyses, share information, having meetings in VR with INFINITY. It implies various interfaces and features to perform tasks. The events (cybercrime and terrorism) are extreme, usually characteristic of acute stress at work (Kleber & Velden, 2009). But here, we focus on what can occur while immersed in VR. Therefore, acute stress of weaker intensity than dramatic events directly experienced. We focus on workers using VR to fulfil their investigation's tasks. Those tasks can be mediated by difficulty, the time to fulfil it, and the violence pictured in the media analysed during the investigation. Acute stress, in general, can impair executive functions (Shields et al., 2016). According to LeBlanc (2009), stress reduces selective attention (Bater & Jordan, 2020; K. Lee & Choo, 2013), impairs working memory (see section 3.4 page - 62 - and section 3.5.1.2 page - 83 -), enhances memory consolidation (Roesler & McGaugh, 2019), and impairs memory recall/retrieval (Klier et al., 2020; Staresina & Wimber, 2019). Therefore, we can infer that stress could impair work performance when fulfilling tasks in VR depending on task typologies.

Three factors are addressed: techno-stress, noise, and task-related (difficulty, time pressure, and violent contents). These factors encompass variables that can impair task efficiency in VR and influence individual well-being relating to VR use. Hereinafter is described how acute psychological and physical stress can be induced at the workplace when using VR and why it needs to be addressed.

3.3.4 ACUTE STRESS AND WORKING IN VR

3.3.4.1 TECHNO-STRESS

Growing ICT uses at the workplace induce a specific type of stress factors: techno-stress (Brivio et al., 2018; La Torre et al., 2019). Techno-stress refers to (Ragu-Nathan et al., 2008): "*an IT user's experience of stress when using technologies.*" It has been observed with the introduction of many ICTs in the workplace over the years (Karimikia et al., 2020; Tarafdar et al., 2015; B. Wang et al., 2020). Techno-stress can lie on the Transactional Theory of Stress (Zhao et al., 2020) presented here in above. La Torre et al. (2019) list five factors contributing to techno-stress. We specifically concentrate on techno-complexity. Techno-complexity defines the inherent quality of an ITC, which drives employees to feel that their computer skills are inadequate. Symptomology is poor concentration, irritability, memory disturbances as well as exhaustion. Since VR at the workplace is new for most workers, it is reasonable to presume it could lead to techno-complexity stress. LEAs will have to constantly learn how to use this ICT (Tarafdar et al., 2019). VR might replace part of existing ICTs. However, it might add to and result in in techno-overload: "*simultaneous, different streams of information that increase the pace and volume of work*" (Atanasoff & Venable, 2017). Inside this techno-overload, the "information overload" dimension (Nisafani et al., 2020) could apply in the context of data analyses by LEAs in VR. Since VR is new for most workers and implies side effects, we can predict a high demand both psychologically and physiologically (Atanasoff & Venable, 2017; Zhao et al., 2020). However, VR is not considered in overviews about techno-stress (Bondanini et al., 2020; Karimikia et al., 2020). But coping with VR induced techno-complexity could result in stress responses (Dragano & Lunau, 2020; Tarafdar et al., 2020; Weinert et al., 2020) described in the previous sections. The dynamic to have workers in a virtual office can facilitate such techno-stress (Stich, 2020).

Ultimately, techno-stress could negatively impact performance in general and at the task level (Nisafani et al., 2020; Tams et al., 2018).

In summary, techno-complexity is critical as 1) it could make VR perceived as non-efficient to fulfil tasks (from INFINITY scenarios), 2) it could impact task performance itself, 3) VR could be an additional stress source that impacts negatively workers well-being. This should be considered with caution while designing the immersive environment and implementing it (e.g., training sessions, support to the user when needed). This will be further addressed in D2.2.

3.3.4.2 NOISE

The work environment can impact occupational stress and psychological stress (de Ramón-Fernández et al., 2017; Kou et al., 2020; Sander et al., 2019). We decided to concentrate on one stressor: noise. In daily life and, for our specific focus, working environment, acute noise is present and impacts negatively human activities (Marsh et al., 2018; Mohamed et al., 2021; Radun et al., 2020; Reinten et al., 2017; Szalma & Hancock, 2011; Vasilev et al., 2018). Noise, especially sudden noise, induces a stress response in humans (Dampney, 2019). However, noise exposure doesn't always elicit significant cortisol response (Dickerson & Kemeny, 2004) or other physiological responses (Clausen et al., 2013; Kristiansen et al., 2009; Love et al., 2018) and is little used as a stressor (Kristiansen, 2010; Plieger & Reuter, 2020). Usually, noises over 80 dB are problematic (Bolm-Audorff et al., 2020). Here, we focus on open-plan offices, which are becoming standard and where workers are often exposed to noise (Huimin et al., 2019). In an office, we can speculate the noise is intermittent (Reinten et al., 2017): speech, phones ringing, software sound design, typing, printing, and walking sounds. These noises contribute to stress at the workplace (Jahncke & Hallman, 2020). Background noise in an office and conversation ranges from 50 to 70 dB (Abouee-Mehrizi et al., 2020). The speech noises irrelevant to a given task, and unpredictability impair task performance (Marsh et al., 2018; Szalma & Hancock, 2011; Vasilev et al., 2018). Noise contributes to distraction and disturbance (Abbasi et al., 2020; Jahncke & Hallman, 2020; Minutillo et al., 2021; Vasilev et al., 2018).

However, no previous works directly tackle noise as an acute stressor while using VR and its impact on task performance in VR. But in INFINITY, workers collaborate in the same virtual environment. They talk and share information. Thus, the literature about open-plan offices informs us how speech noises could be a stress factor that impacts task performances while in VR. Contributions in surgery can also inform of the impact of noise and irrelevant communication (51dB to 79dB about the same range as in an office) on performances that are both harmful to surgical performance (Mcleod et al., 2021). When performing surgery, noises can disturb and negatively impact task performances (C. Yang et al., 2017). We hypothesize that noises in VR while working, such as speeches from other users, could disturb and distract. Therefore, it could be challenging for workers to cope with such physical stress and lower their task performances.

In summary, noise in a shared VR environment could distract and disturb LEAs' work. Noise has to be considered a stress factor that can impact performance in VR and workers' well-being.

3.3.4.3 EXPOSURE TO DISTRESSING MATERIAL AND SECONDARY TRAUMATIC STRESS

In INFINITY, investigations are taking place during cyberattacks and after terrorist attacks. It implies exposure to violence (events, texts, images, sounds, and videos) (Violanti et al., 2017). Exposure to threatening, violent or negative material is known to activate stress (S. E. Williams et al., 2017). Stress, which is also seen as negative emotions, is often induced via such media for in-lab experiments (Ack Baraly et al., 2020; Bradley & Lang, 2007; Child Nicholas et al., 2014; Stevenson et al., 2007; W. Yang et al., 2018). When such emotions are induced, it can impact task-related cognition (Carretié, 2014). As a first approximation, we can hypothesize that exposure to violent media provokes the stress process. Therefore, it can change the user's state when confronted with it. Terrorist attack images are collective trauma that induce acute stress (e.g., the Boston Marathon bombings) in the general population (Holman et al., 2020; Thompson et al., 2019). For analysts, such disturbing media are known to be a source of stress (e.g., internet child pornography) (Holt & Blevins, 2011; Perez et al., 2010). Exposure to those types of media can induce Secondary Traumatic Stress (Ludick & Figley, 2017; Molnar et al., 2017; Sprang et al., 2019). Secondary traumatic stress is defined as (Baird & Kracen, 2006): "*psychological symptoms that mimic post-traumatic stress disorder, but is acquired through exposure to persons suffering the effects of trauma.*" Those symptoms apply to law enforcement (Craun et al., 2014; Denk-Florea et al., 2020; Landers et al., 2020; Violanti et al., 2017). It can even apply to lawyers (Benuto et al., 2018; Weir et al., 2020). Interestingly, perceived and job-related psychological stress is more significant for Forensic Technicians than Sworn Police Officers when exposed to violent crime scenes (including appalling imagery) (McKay-Davis et al., 2020). Analysts might not be directly exposed to the violent content of crime scenes like crime scene technicians are (Mrevlje, 2016; Sollie et al., 2017).

Concretely in INFINITY, with the use case regarding cybercrime, analysts can be exposed to media showing distressing situations such as company activities, people's emotional reactions, and money extorts from attacked people (Backhaus et al., 2020; Stacey et al., 2021). With the use case of post-terrorist attacks, analysts can be exposed to dead bodies, gunshots, people in fear and terror etc. (Foley et al., 2021). If images are coming from co-workers, analysts can witness team members exhibiting acute stress reaction as in militaries (Svetlitzky et al., 2020) or among first-responders (Alrutz et al., 2020) and also during the aftermath of terrorist attacks (Motreff et al., 2020). Proper training and desensitization with time may reduce risks for police workers to present Secondary Traumatic Stress and cope with it (Fortune et al., 2017; Grant et al., 2019; Perez et al., 2010). However, while working in VR, distressing material might induce acute stress that workers need to cope with while performing tasks.

In summary, analysts in INFINITY use cases must cope with various disturbing material going from crime scenes, after terrorist attacks, to the emotions of victims of cyber-attacks. These disturbing materials are stressors that can lead to secondary traumatic stress. It seems legitimate to hypothesize that such induced stress could impair task performances while in VR. However, no direct scientific work seems to tackle this issue. But generally observed effects of stress over performance could be applied to that specific source of stress.

3.3.4.4 TASK DIFFICULTY

The amount of data (Marciani et al., 2017; Neto, 2017; Sanders & Condon, 2017; Tyagi & Sharma, 2020) to consider for investigations implies high task difficulty (Alison & Ask, 2010; Hadlington et al., 2018; Harkin et al., 2018; Nouh et al., 2019; Pramanik et al., 2017). Difficulty can be approached via the concept of task load. Zimmerman (2017) defines task load has: "*a measurement of human performance that broadly refers to the levels of difficulty individual encounters when executing a task.*" It is the function of three factors: "*time taken to perform a task, level of information processing, and number of task switches that occur in the context of task performance.*" Therefore, task load encompasses multitasking (Plessow & Fischer, 2017). Multitasking can negatively impact task performance (Modi et al., 2020). Stress and task difficulty impact cognition (Y. Kim et al., 2017). The difficulty of a task is usually approximated through response time and accuracy (Gilbert et al., 2012). A challenging task induces a higher focus on accomplishing it. Still, performance of the task can decrease with lower dominance over it, faster breathing, and higher skin conductance levels (Caldas et al., 2020). Depending on the level of mental workload (dependent time pressure and task difficulty (Galy et al., 2012), see section 3.4 page - 62 -) and stress, despite a link between difficulty and repetition rate, difficulty can also enhance task performance or not change performance (Main et al., 2017; J. Song et al., 2011). Difficulty due to stressors increases task errors with examples in laparoscopy (Moorthy et al., 2003). De Dreu et al. (2019) show that task difficulty implies the lowest performances and higher response time. Still, performance is facilitated by expectations about the difficulty of an upcoming cognitive challenge in the brain.

Using VR rather than classical paper-and-pencil or computerized measures to perform neuropsychological assessments revealed an increased level of complexity and difficulty, which suggests VR requires additional cognitive resources (Neguţ et al., 2016). Interestingly, Neguţ et al. observe that the most substantial effect is measured with healthy participants (compared to clinical participants). Therefore, we can hypothesize that tasks in VR should be seen as potentially tricky only based on apparatus. The surgery literature shows clearly that the complexity of tasks increases mental workload (Bretonnier et al., 2020). The more task load requires cognitive resources, the more it can be challenging, perceived difficult for humans to fulfil a task, and, therefore, a source of stress.

In summary, task difficulty influencing task performances negatively becomes harmful on the investigation's potential quality, ultimately related to money losses and more victims. Hence, task load in VR should be controlled to allow optimal time on task and performance. Otherwise, it can reveal to be a stressor that impacts analyst's work performance.

3.3.4.5 TIME PRESSURE

Any investigation, primarily if occurring during cybercrimes and right after terrorist attacks, implies an intense time pressure because of high time urgency (Alison & Ask, 2010; Brown et al., 2020; Power & Alison, 2017). Time pressure defines an (Denovan & Dagnall, 2019): "*insufficient time available to complete necessary tasks*." This insufficient time available is an individual perception of the amount of time necessary to fulfil a task (Ordóñez et al., 2015). In the literature, time pressure is usually approached as a chronic stressor at the job level. It is a challenge stressor that can be coped via extra efforts, leading to strain and exhaustion (Prem et al., 2018). Police workers are exposed to that stressor (Garbarino & Magnavita, 2015). But here, we focus on time pressure relating to a task window in VR. Caviola et al. (2017) analyse that, under time pressure, preferred "*strategies that can be applied rapidly represent the more appropriate choice*" to solve math problems, but that can impact performance negatively. Those math problems rely heavily on working memory capacities like an investigation where analysts must follow a hypothesis. Time pressure during investigations reduces the number of hypotheses tackled (Alison et al., 2013; S. Kim et al., 2020). Time pressure can be a stressor that impairs performances (less with procedural tasks) (McCoy et al., 2014; Prasad et al., 2020). Although time pressure might not consistently lower decision accuracy, e.g., based on uncertainty visualizations of maps, it can impact response time (to make a decision) (Korporaal et al., 2020). While defining deadline has appositive effect on decision making, taking decisions under time pressure is usually presented as having a negative impact (Ordóñez et al., 2015). Time on task impacts physiological variations relating to stress (Heikoop et al., 2017). Here again, surgery literature informs us that time pressure has a negative impact on performances (Arora et al., 2010) and decision making (Modi et al., 2020). Time pressure can also negatively impact dentist's diagnostic performance (Plessas et al., 2019).

In summary, time pressure can be seen as a stressor that would restrict the number of a hypotheses an analyst can investigate related to cybercrime or a terrorist attack (e.g., not following certain clues or links between events/patterns help to catch or identify criminals). Therefore, time pressure impact in VR work should be monitored.

3.3.4.6 PUBLIC SPEAKING

In INFINITY, users will collaborate, present graphs, ongoing investigations, debate with peers, and ultimately solve crimes. We can infer that recurring meetings shall occur similarly to large companies (de Buck, 2007;

Niemantsverdriet & Erickson, 2017). During those meetings, analysts or other police workers need to speak in public. Depending on workers, one can suffer from public speaking anxiety, common in the general population (Ebrahimi et al., 2019; Gallego et al., 2021; Marcel, 2019). Public speaking is well known to induce acute stress, even in healthy adults without public speaking anxiety, and is used with the Trier Social Stress Test (TSST) to study stress in-lab (Allen et al., 2017; Labuschagne et al., 2019; Narvaez Linares et al., 2020). Immersive virtual environments replicating the TSST showed a higher cortisol reactivity than non-immersive (Helminen et al., 2019; Zimmer et al., 2019). Stress-induced with the TSST can impact decision making (Pabst et al., 2013). In a European context, these meetings can be in English like in multinational corporations in which workers present foreign language anxiety (Aichhorn & Puck, 2017; Kelsen, 2019; R. Kim et al., 2019). Presentations in front of peers, debating and, decision making (about the investigation or what to do for the investigation to succeed) in that context can be seen as a stressor. It applies in VR (Barreda-Ángeles et al., 2020).

In summary, public speaking induces the stress process. Therefore, it should be considered as a stressor that can affect law enforcement workers in INFINITY.

3.3.4.7 SUMMARY OF STRESS RISKS WHEN WORKING IN VR

The context of cybercrime and counter-terrorism create a somewhat stressful work environment considering what is at stake. Introducing virtual reality as a new ICT tool can be influenced by stress factors. Since encompassing every factor is too complex, we chose to concentrate on six of them:

- Techno-stress with techno-complexity and techno-overload which directly related to user’s experience of the hardware and software
- Noise with disturbing discussions in VR or interfaces/outside noises like in an open-plan office
- Exposure to distressing materials that can lead to secondary traumatic stress
- Task difficulty with a large amount of data to process during the investigation
- Time pressure with the user’s perception of too little time to fulfil a given task
- Public speaking

Those stressors are to be considered acute. In INFINITY, we are primarily interested in what happens while LEAs are working in VR. However, it is interesting to consider how VR and tasks in VR could participate in chronic stress. Episodic exposure to such stresses should be seen as risks in general (see section 3.3.1 page - 53 -), leading to occupational stress with all its adverse impacts on workers’ health. Occupational stress (Landsbergis et al., 2017) usually is the term used to define stress at work. But occupational stress is chronic (Horan et al., 2020; Quick & Henderson, 2016). Therefore, it does not apply to our scope as we are in a narrower window in which only acute or episodic stress is at stake. Ultimately part of the described stressors can impact decision making (Phillips-Wren & Adya, 2020). Applied to INFINITY, this may concern, for example: what to do to pursue the investigation, what resources to assign to a given investigation, are troop intervention needed etc..

The context of INFINITY will allow measuring the effects of several stressors related to tasks in VR. Measures can apply to what happens in VR. Therefore, it will help to assess acute stress. Ultimately, it could describe how those stressors can become chronic through episodic exposure, feeding occupational stress. In the short term, those stressors can negatively influence work performances, and INFINITY use-case performances since stress impacts cognitive resources necessary to interact with a virtual environment and conduct investigation-related tasks (data processing, meetings, decision making etc.).

3.4 MENTAL WORKLOAD

3.4.1 MENTAL OVERLOAD AND WORKING IN VR

Depending on tasks and the user's cognitive resources, working in VR can require varying amounts of working memory (Burcher & Whelan, 2019; Sanders & Condon, 2017). LEAs, especially analysts, must deal with large data sources, complex visualizations, and the use of sophisticated algorithms to do their work. It is considered to be a complex activity, with a high decision making and problem-solving latitude, dealing with numerous, simultaneous and unpredictable variables (Smith et al., 1995). Workers using INFINITY may have to multitask when they may be required to conduct meetings and present data or investigation reports simultaneously. Depending on the users' relations with the task (motivation), their ability, and difficulty, VR as an apparatus itself could lead to mental overload (Dehais et al., 2020). This could negatively impact their work performance within the VR environment and cause episodic exposure to issues at the occupational level.

In this section, we first provide an overview of the concept of mental workload. Secondly, we describe factors that make mental overload occur. Finally, we present contributions showing how mental overload can arise when working (or performing similar tasks) in VR.

3.4.1.1 MENTAL WORKLOAD OVERVIEW

Cognitive load and mental workload are often used as synonyms in literature (Van Acker et al., 2018). The cognitive load concept is used in the learning field, whilst the mental workload is used in ergonomics / human factors (Orru & Longo, 2019). Vanneste et al. (2020) mention that despite differing definitions, the two concepts share a common ground: the amount of working memory resources used for a given task (Baddeley, 2012; Leppink, 2017). These working memory resources are limited (Adams et al., 2018; Camina & Güell, 2017; Chai et al., 2018). As described by Eriksson *et al.* (2015), "*working memory maintains information in an easily accessible state over brief periods of time (several seconds to minutes)*" for use in an ongoing task (see **Erreur ! Source du renvoi introuvable.** page - 63 -). The aspect of reference to limited working memory resources is based on the *Multiple Resource Theory* stating that (Basil, 2012): "*People have a limited set of resources [pool of energy] available for mental processes [operations, from sensory-level processing to meaning-level processing] [that] are allocated across different tasks, modalities, and processing*."

The concept of mental workload is used as defined by van Acker et al. (2018): "*Mental workload is a subjectively experienced physiological processing state, revealing the interplay between one's limited and multidimensional cognitive resources and the cognitive work demands being exposed to.*"

This definition and the concept of mental workload and aligned it with findings of ergonomics and human factors as we investigate work-related tasks. However, previous contributions using cognitive load concepts are as well given detailed consideration in the following sections when employed in work-related contributions. Numerous theories of mental workload compete and ad-hoc definitions and frameworks are proposed in the literature (Dehais et al., 2020; Vanneste et al., 2020). Synthetizing 82 previous works, Van Acker et al. (2018) propose an explanatory framework of mental workload that we reproduced in Figure 26 page - 63 -.

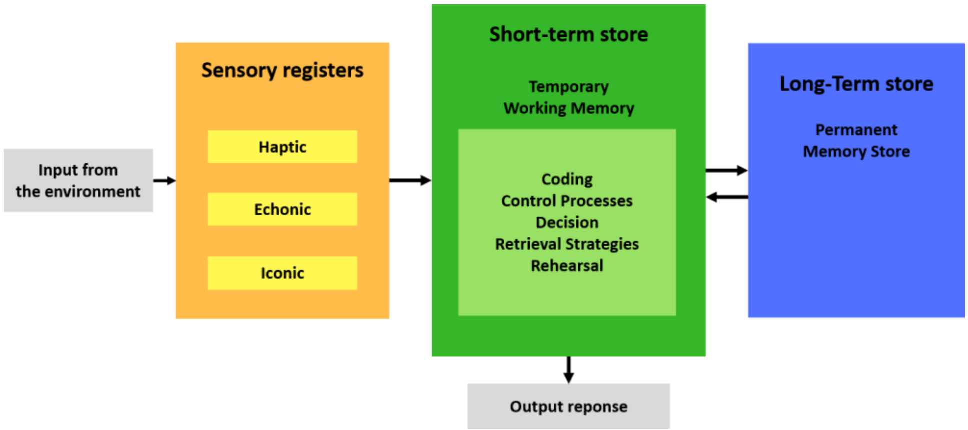


Figure 25: Memory model by Camina and Güell (2017)

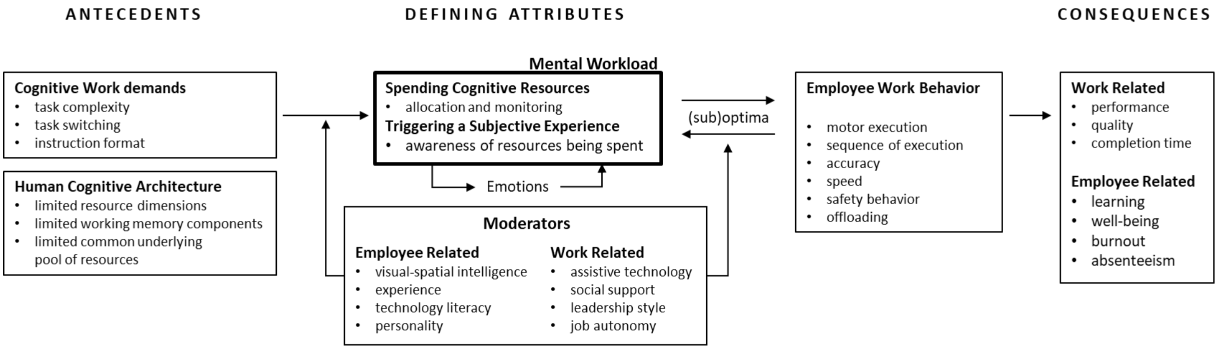


Figure 26: Explanatory framework of mental workload consisting of antecedents, defining attributes and consequences, extended with emotions, moderators, and employee work behaviour, Van Acker et al. (2018)

This framework by Van Acker et al. (2018) gathered common predictive components of mental workload in work-related tasks at an occupational level. The introduction of VR as an extra apparatus of the workstation for analysts and other police workers could be expected to have specific impacts in the three categories conceptualized in the framework: antecedents, defining attributes, consequences. In INFINITY, we are interested in consequences of VR use. Therefore, we do not apply the Van Acker et al. framework at the occupational level but at the VR use level. We concentrate on how working memory can be overloaded, impacting task performances, quality, completion time (work-related in Van Acker et al. (2018) framework). Mental workload seems dependent on cognitive work demands (Causse et al., 2017) and resource consumption. Two demands are often referred to: time pressure and task difficulty/complexity (Galy et al., 2012). However, time pressure is not listed in Acker et al.'s (2018) framework. In the previous section about stress and working in VR, we showed that those two factors also induce stress.

3.4.1.2 MENTAL OVERLOAD OCCURRENCE

Depending on task characteristics, workers can face suboptimal levels of mental workload: underload and overload. M. S. Young et al. (2015) indicate that overload "*occurs, for instance, when the operator is faced with more stimuli than (s)he is able to handle while maintaining their own standards of performance.*" Conversely, M. S. Young et al. (2015) describe that "*too little stimulation can lead to underload, as resources are either allocated elsewhere or otherwise shrink through underuse*." For M. S. Young et al., these variations that can lead to non-optimal working memory resource allocation which is dependent on task engagement. Overload and underload are mismatches between demands and capabilities, which means that reducing mental workload of a given task might not be a good strategy.

The most commonly accepted hypothesis describes the relationship between mental workload and performance through an ''inverted U-shape," which is disputed (Babiloni, 2019: see Figure 27 page - 64 -).

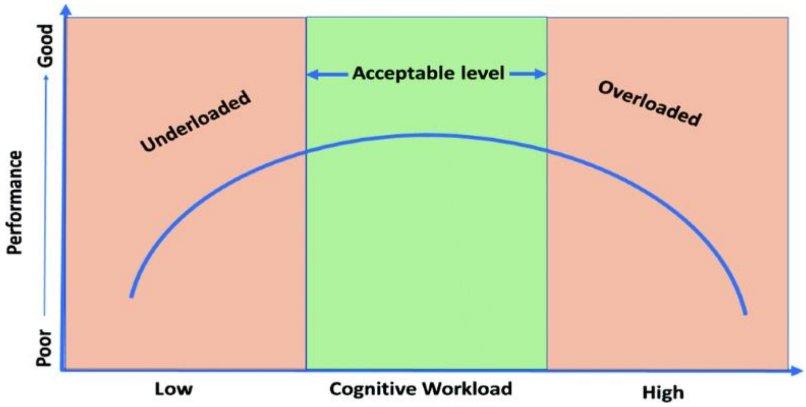


Figure 27: Inverted U-shape relationship between mental workload and performance, Babiloni (2019)

M. S. Young et al. (2015) propose an updated representation of relationships between performance, task demands, and resource supply. This representation allows drawing mental workload variation (see Figure 28 page - 64 -). High task demand, increasing resource demand, does not constantly impact performance negatively. Researchers rarely concentrate on mental underload as the concept is difficult to be defined and explained correctly (Sharples, 2019; M. S. Young et al., 2015). Mental workload is also dependent on attention (Curtin & Ayaz, 2019; Sepp et al., 2019) or engagement (Dehais et al., 2020).

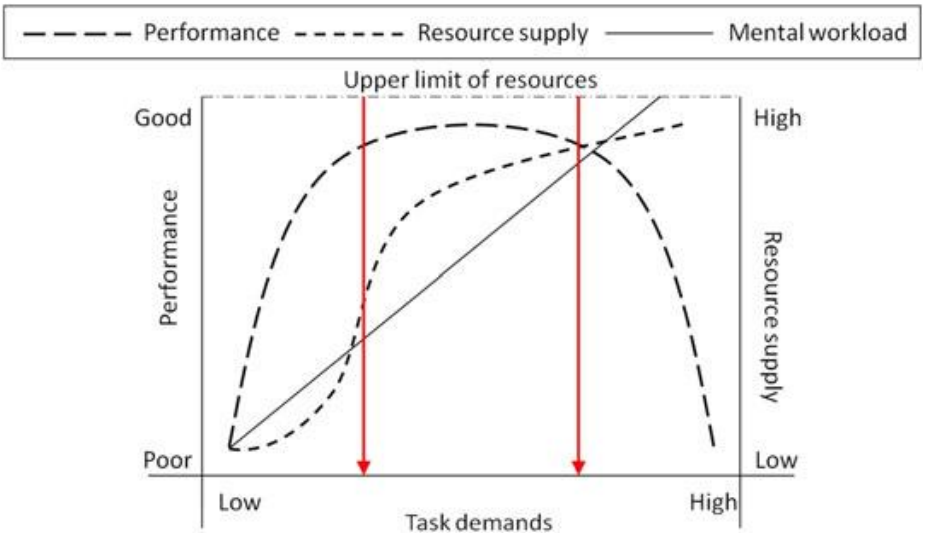


Figure 28: M. S. Young et al. (2015) interprets the supply-demand relationship associated with mental workload and performance, highlighting the redlines of overload and underload. Left of the first redline, an increase in resource supply and mental workload increases performance ('reserve capacity' region). Right of the second redline, an increase of resources supply and mental workload decrease performance ('overload region').

According to Dobryakova *et al.* (2013), cognitive fatigue is the inability to maintain cognitive performance due to mental exhaustion. Performance is lower or more variable with an individual's optimal abilities (Holtzer et al., 2010). According to Van der Linden (2011), cognitive fatigue is temporary, and the optimal abilities can be recovered: e.g., by changing tasks. Therefore, we note that cognitive fatigue is globally describing similar "conditions" to cognitive overload.

Since mental overload is highly contingent on the tasks, it is difficult to be explained by a general model. Examples exist in air traffic control (Tobaruela et al., 2014), driving (Paxion et al., 2014; Wickens, 2017), and work in nuclear power plants (Lim et al., 2013). Lim et al. (2013) proposed a model that is, generic enough to provide an overview of mental overload factors. However, this model has been developed to prevent human error in nuclear power plants (see Figure 29 page - 65 -).

Based on the model by Lim et al., three categories of factors can affect mental workload: 1) task and environmental factors (interestingly we find noise as an example, see section 3.3.4.2 page - 58 -), 2) Operator's characteristics and moderating factors, 3) Difficulty, response, and performance. Twenty-four factors can ultimately impact performance at completing a task in this model.

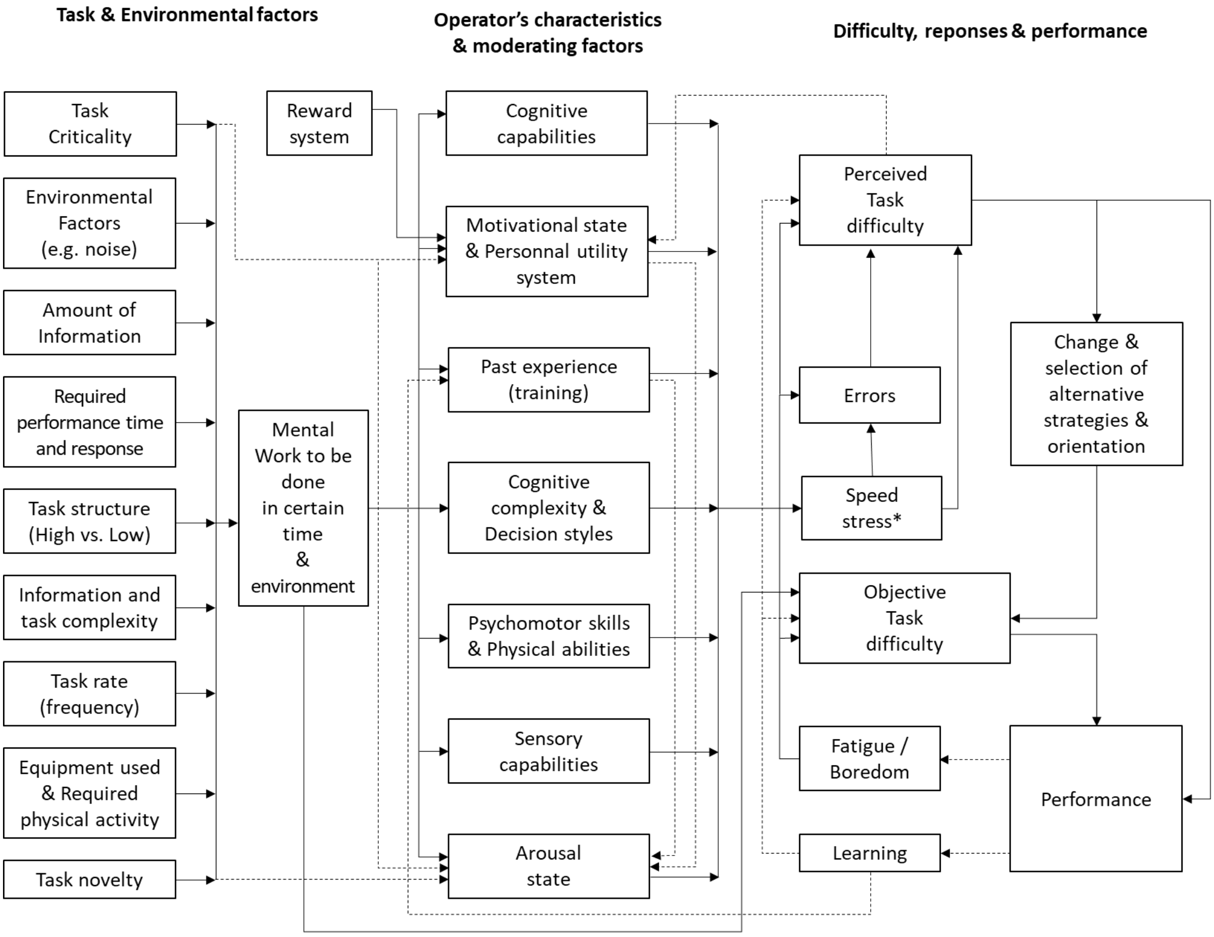


Figure 29: Major components of the comprehensive mental workload model (the original model also presents related assessment variables to the right, which have been deleted in the current reproduction), *Speed stress can also be interpreted as time pressure, Lim et al. (2013)

In summary, mental overload can occur when performing a given task, leading to non-optimal working memory resource allocation, depending on task demand (mismatch between demands and capabilities), which reduces performance. Mental overload occurs depending on: 1) intrinsic task load, 2) users' characteristics, 3) feedback, coping strategies depending on the task, which finally impacts performance.

3.4.1.3 MENTAL OVERLOAD AND WORKING IN VR

Oculus recently have spoken about “Infinite Office,” a virtual office space (Oculus, 2020). However, scientific knowledge regarding a VR office, especially the possible consequence on mental workload, seem rare. Other contexts, close to typical tasks that occur would be performed in such a virtual environment, are presented hereafter. The work context includes interaction with 3D objects, information spatialization, text entry, recalling procedure and interface to realize a task, reading, editing several media to present them. In Table 11 page - 66 - we summarize 20 studies that analysed mental workload in VR. We concentrate on tasks comparable to what working in VR could imply for INFINITY: that being desktop-like tasks and data visualization and analytics.

Table 11: VR impacts on mental workload depending on tasks that are comparable to what working in INFINITY would require from users (video games that require interactions or stimuli too far from tasks an analyst might encounter in VR have been excluded

Reference	Task	Mental workload impacts	HMD
(S. Zhang et al., 2017)	Flight simulation	Higher mental workload in VR than with PC	Oculus rift
(Filho et al., 2018)	Data visualization and analytical tasks	Higher mental workload in VR than with PC but equivalent performance	Oculus rift
(Geiger et al., 2018)	Object grasping	Picture + Hand Color Feedback as an interaction metaphor and feedback drives to a lower mental workload compared to Picture Feedback without additional color and Picture + Object Color Feedback	HTC Vive
(Knierim et al., 2018)	Text entry on a keyboard with or without hand representation	Text entry without hand representation leads to higher mental workload, and realistic hand representation leads to the lowest mental workload	Oculus rift
(Speicher, Hell, et al., 2018)	Pointing and grasping objects in a shopping experience	Grab leads to higher physical demand than beam and results in higher mental workload (frustration)	HTC Vive
(Speicher, Feit, et al., 2018)	Text entry on a virtual keyboard	Mid-air interaction techniques lead to higher mental workload due to physical demand	HTC Vive
(Wismer et al., 2018)	Learning 3D brain anatomy	VR leads to a higher objective but lower subjective mental workload than a plastic physical model	HTC Vive
(Aksoy et al., 2019)	Training at basic life support procedure	Mental workload decreases with task familiarity and practice	HTC Vive
(Armougum et al., 2019)	Navigation in a tube station, spatial orientation	Experts of the station and line present a lower mental workload than novices	HTC Vive
(Bernard et al., 2019)	Helicopter maintenance tasks	VR leadsleads to higher mental workload than physical simulation	Oculus rift
(Broucke & Deligiannis, 2019)	Geographic (city) data visualization and interaction: finding information	Mental workload in VR and on PC are equivalent	Oculus Rift
(Luong et al., 2019)	N back tasks - 3 levels of difficulty	Natural Walking leads to higher mental workload while performing the task	HTC Vive

(Makransky et al., 2019)	Lab cell culturing, cell transfection, and protein expression for mammalian transient protein expression learning	VR leadsleads to higher mental workload (and a decrease in knowledge acquisition) compared to PC	Samsung GearVR with Samsung Galaxy 6
(Biener et al., 2020)	Content transfer task and Puzzle task with different interaction metaphors and interfaces	Content transfer: Gaze-based interaction faster than bimanual with similar performances. Gaze-based interaction shows a lower mental workload than bimanual. Puzzle: Depth visualization faster than Flat but with more errors. Flat visualization leads to higher mental workload than depth. The higher the number of layers, the higher mental workload.	HTC Vive Pro Eye
(Gupta et al., 2020)	N back tasks – 2 levels of difficulty, with or without the help of a virtual agent	Mental workload is higher when tasks indications by the agent are inconsistent	HTC Vive
(Filho et al., 2020)	Geo-visualisation and Trajectory Data Exploration (Space-Time Cube)	VR leadsleads to lower mental workload than PC	Oculus Rift
(Baceviciute et al., 2021)	Reading (about sarcoma cancer) and learning test (Paper versus VR)	VR requires more cognitive effort than paper and takes more time to fulfil the task but leads to higher transfer	HTC Vive
(Gao et al., 2021)	Recalling spatial location of icons on a grid with or without audio-visual landmarks	Audio-visual landmarks lead to require lower mental workload	HTC Vive
(Tian et al., 2021)	Film editing (PC versus VR)	The faster the cutting rate, the higher the mental workload. VR leads to a higher workload than PC	HTC Vive
(H. Wu et al., 2021)	Grabbing objects (eyes-free spatial target acquisition)	Lower mental workload with virtual balls in the front and middle layers in the horizontal axis and the middle layer in the vertical axis. Targets in the far layer caused the most negligible task load. Targets on the right side caused a lower task load (for right-handed people).	HTC Vive

Six of the above studies compare PC to VR (S. Zhang et al., 2017; Broucke & Deligiannis, 2019; Makransky et al., 2019; Tian et al., 2021), which is relevant in our use-case scenarios as in INFINITY, we propose to replace current tasks completed on a PC by VR partially. Contradictory results regarding mental workload are observed. Sometimes VR decreases mental workload, usually when tasks rely heavily on spatial orientation and interaction. Sometimes VR increases mental workload: Filho et al. (2018) directly investigate similar issues as encountered in INFINITY by creating "VirtualDesk," which consists of data visualization and analytics. Mental workload appears similar in VR than on PC for a typical analyst's tasks. But for geo-visualisation and trajectory data exploration, VR presents a lower mental workload than PC (Filho et al., 2018, 2019, 2020).

Five studies experiment with various HCI aspects which show that independent of the task goal, the interface and interactions already impact mental workload (Geiger et al., 2018; Speicher, Hell, et al., 2018; Zielasko et al., 2019; Biener et al., 2020; Gao et al., 2021; H. Wu et al., 2021). It appears that assistance within the interface helps to reduce mental workload and promote higher performance in VR (Geiger et al., 2018; Gupta et al., 2020; Gao et al., 2021). The physical efforts a task requires may also impacts mental workload: e.g., text input posture and required movement (Knierim et al., 2018; Speicher, Feit, et al., 2018).

Research literature that assesses mental workload in VR is still very rare. Therefore, it would be inappropriate to generalize the present results to the workplace tasks context and, in our case, to LEAs typical tasks. However, the presented studies give an insight into the effects of VR on mental workload. Taking advantage of spatialization possibilities within VR seems to reduce mental workload if tasks require such cognitively-related resources (Armougum et al., 2019; Broucke & Deligiannis, 2019; Filho et al., 2018, 2020; Wismer et al., 2018). For example, the literature finds that information presented in the same time and space has a positive impact on problem solving, by decreasing the split attention effect (Gines, 2006). The temporal and spatial contiguity (Mayer, 2017) can help the user to avoid maintaining information in memory during the time and space while they search for other potentially related information. The extraneous load is facilitated by helping the activity of understanding relations between information and schema construction, presenting information easily. Users are limited in the real world by the constraint of the physical space. In contrast, a virtual and immersive environment can support the user with temporal and spatial contiguity, by overcoming the limitations of the physical world. Information can be displayed all around the LEAs to help to provide better common situational awareness for example, or they can go into the data or graphics to have better understanding of them (Cavallo & al, 2019). With regards to the activity of data analysis, recent research focuses on how VR and AR can be instrumental in supporting complex data analysis, by investigating a large dataset simultaneously and helping the user to quickly see the areas of interest, anomalies, and structures. (Butscher & al, 2018).

On the other side, VR seems to lead to mental overload when tasks are performed that do not require such spatialization cues or interactions and when they are too far from what users are accustomed to (Baceviciute et al., 2021; Bernard et al., 2019; Wismer et al., 2018). Those results seem to be moderated by expertise within VR and the task demands (Aksoy et al., 2019; Armougum et al., 2019; Luong et al., 2019). For instance, outside of VR, when time and load on the resources are high, which hits the maximum resource allocation capacity (McGregor et al., 2021).

3.4.1.4 SUMMARY OF MENTAL OVERLOAD AND WORKING IN VR

Working in VR within cybercrime and counter-terrorism requires interaction with various data sources and performing tasks which would typically be performed on a PC. Introducing VR as a new ICT tool requires changes in terms of interaction and interfaces. Therefore, expertise within VR and understanding new ways of fulfilling tasks could impact mental workload. But interaction and the interface themselves could lead to mental overload because they seem they require higher working memory resources. It appears that typical tasks transposed in VR do require more working memory resources, such as reading and writing with a keyboard. However, VR allows information spatialization. Despite requiring higher working memory resources, such spatialization seems to promote high performance when tasks take advantage of spatial information. Typically, data visualization and analytics seem to work well in VR because of these spatial information possibilities.

The current state of the art regarding working in VR and its effects on mental workload lacks contributions directly assessing this context. Looking at comparable tasks, the impact of VR on mental workload is mixed and sometimes contradictory. Consistent findings are that mental workload in VR seems higher than in other apparatuses. However, this does not always impact task performance negatively. Furthermore, workers' expertise, regarding both VR and the tasks they are performing influences performance, objective, and subjective mental workload. Several studies directly tackle data visualization and analytics relevant to the INFINITY project as the central position will be the analyst.

INFINITY pilot tests should systematically measure mental workload using including the use of questionnaires to better understand and delimit the effects of working in VR for LEAs over working memory resources, compared to traditional PC-based work. Poor or inadequate interaction methods and interfaces could lead to mental overload and decrease task performance. Furthermore, analysts and other LEA workers could put VR aside when high time pressure and task load require high performance if VR causes mental overload. However, for the time being this present time, little scientific data can generalize those predictions. Therefore, INFINITY should concentrate on directly studying VR work impacts on mental workload. Since previous sections also presented other side effects or negative impacts that could arise with VR, possible working memory resources saturation provoked by cybersickness, visual fatigue, and acute stress should also be considered. It could impact the total amount of available resources and reduce the user's ability to allocate sufficient resources to tasks in VR (see section 3.5.1 page - 83 -).

3.4.2 MEASURING VR SIDE EFFECTS, ACUTE STRESS, AND MENTAL OVERLOAD

3.4.2.1 INTRODUCTION

The negative impacts of performing tasks in VR and HMDs on ergonomic factors can be measured. However, the best tools, questionnaires, and statistical analysis strategies are still open research questions. Physiological sensors are available, namely: eye-tracking, pupillometry, electrocardiogram (ECG), and electrodermal activity (EDA). They are pointed out as efficient tools to measure cybersickness, visual fatigue, stress, and mental workload in 26 reviews, systematic reviews, or meta-analysis (Dirican & Göktürk, 2011; Pedrotti et al., 2014; Mark S. Dennison et al., 2016; Wickens, 2017; Butmee et al., 2018; Elzeiny & Qaraqe, 2018; Dias et al., 2018; H.-G. Kim et al., 2018; Marinescu et al., 2018; Rastgoo et al., 2018; Arza et al., 2019; Carneiro et al., 2019; Charles & Nixon, 2019; Hughes et al., 2019; Koohestani et al., 2019; Matsuura, 2019; Tao et al., 2019; Y. Wang et al., 2019; Armario et al., 2020; E. Chang et al., 2020; Kemeny et al., 2020; Lopes et al., 2020a; McNamara & Mehta, 2020; Nath et al., 2020; Stanney, Lawson, et al., 2020; Vanneste et al., 2020; Ishaque et al., 2021; Skaramagkas et al., 2021). Some sensors are already embedded, or are about to be, in consumer HMDs (Clay et al., 2019; Floris et al., 2020). But these sensors measure multidimensional states of the human body. Several indicators can be inferred from signals obtained from such sensors. Therefore, it is hard to decide which sensors and which indicators should be used to assess each state. Although available wearables such as "smartwatches" can measure physiological signals, the quality of recording and available sensors are still not sufficient (Gradl et al., 2019). This section aims to present physiological sensors pointed out in the scientific literature to measure ergonomics-related states. The muscle fatigue aspects are not further examined.

First, we concentrate on eye-tracking and pupillometry. Second, we present ECG. Third, we introduce EDA. Finally, we suggest questionnaires for a subjective measure of cybersickness, visual fatigue, acute stress, and mental workload.

3.4.2.2 EYE-TRACKING AND PUPILLOMETRY

Eye-tracking is a technique used to monitor a user's point of gaze and eye motion (Duchowski, 2017): see Figure 30 page - 70 -. The intention is to measure the user's gaze location in a scene in real-time (Majaranta, 2012) and record visual system behaviours. Video oculography (VOG) (Zemblys & Komogortsev, 2018) is the most common technique. It consists of gaze location estimation, which is carried out based on the pupil's centre-tracking and the corneal reflection of a light emitted onto the eye. This technique has the advantage of being non-invasive and conducted in real-time. But, it involves implementation difficulties (Majaranta & Bulling, 2014). These difficulties include poor accuracy (Dalrymple et al., 2018), loss of tracking, the influence of content (luminance, colours, movements) (Binaee et al., 2016; Goldberg & Wichansky, 2003), and contextual effects related to the apparatus itself (nocebo effect) (Höfler et al., 2018). Therefore, to ensure that the eye tracker does not lose efficiency in tracking, frequent calibrations are necessary (B. T. Carter & Luke, 2020). Eye tracking also requires high energy consumption, a determining constraint, primarily if implemented in HMDs. Variations in eye behaviours depending on individual characteristics, such as age, sex, circadian cycles, health, drug use, or expertise have been documented (Jongkees & Colzato, 2016; John et al., 2018; Marandi et al., 2018; Wardhani et al., 2020). Such variations can also be due to environmental characteristics such as luminosity, noise and temperature (Cherng et al., 2020; John, 2019; John et al., 2018; Silva et al., 2019). This versatility encourages an individual-based approach to perform measurements.

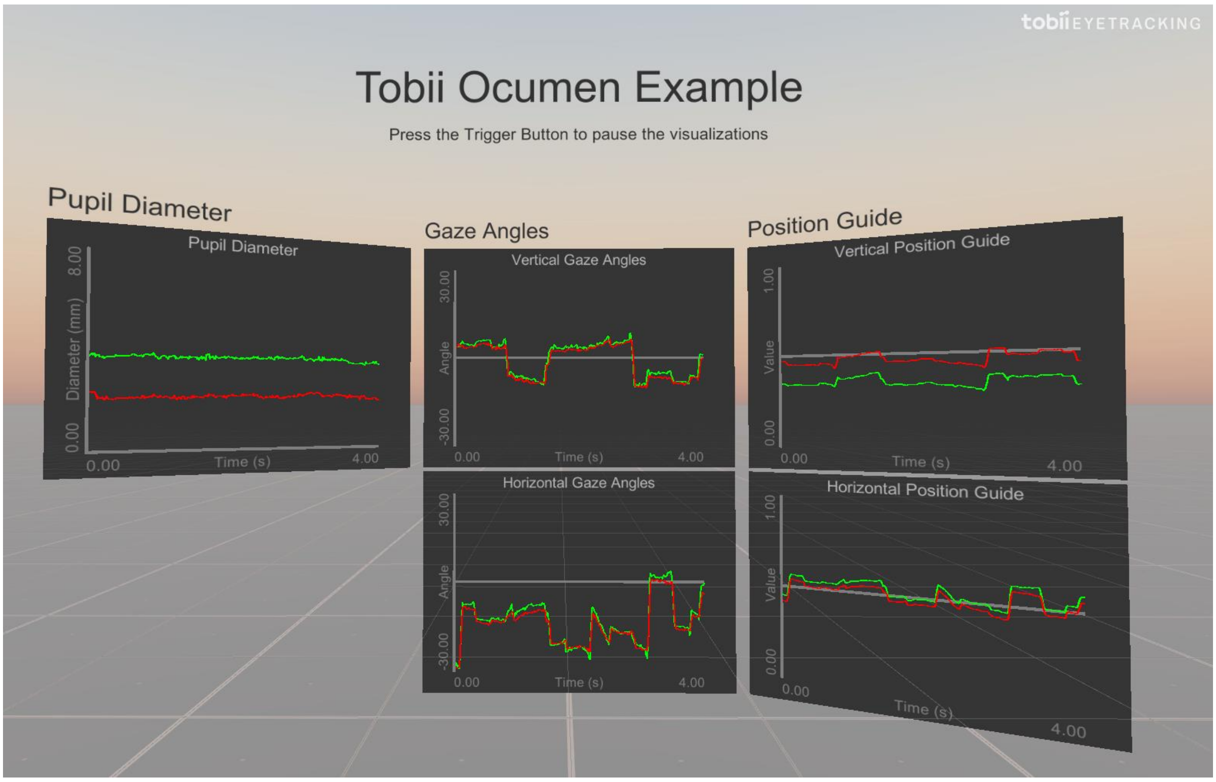


Figure 30: Example of eye-tracking indicators (pupil diameter, gaze angles, position guide), left eye is red, right eye in green © Tobii

Table 12 page - 70 - presents five experiments that use eye-tracking or electrooculography (EOG) to study cybersickness in VR. Blinks are the leading indicator used to assess cybersickness (four out of five). Pupil diameter, fixations, and saccades are also used (one out of five).

Table 12: Five examples of Eye-tracking or EOG used to measure cybersickness

Reference	Eye tracker	Indicators/Features	Device	Tasks	Main results
(Mark S. Dennison et al., 2016)	EL507, BIOPAC Systems, Inc. (EOG)	Blink rate	Oculus Rift	Half-Life 2 game level	More blinks per epoch in HMD than PC Blinks increase with HMD time exposure
(Garcia-Agundez et al., 2019)	g.Tec sensors (EOG)	Blink rate	Oculus Rift	Controlling a plane	Not mentioned
(John, 2019)	SMI RED-m eye tracker	Pupil diameter	Oculus Rift	Not mentioned	Not mentioned

(Lopes et al., 2020b)	Tobii	Blink rate Fixation Saccades	HTC Vive Pro Eye	Explore and collect coins	Sickness increases blink rate and concentrate fixations to smaller areas
(Lopes et al., 2020a)	Tobii	Blink rate	HTC Vive Pro Eye	Explore and collect coins	Sickness increases blink rate

Table 13 page - 71 -, presents five experiments that used eye-tracking or EOG to study visual fatigue in VR and one with a tablet. Blinks are the leading indicator used to assess visual fatigue (five out of six). Pupil diameter, fixations, vergence angles, and saccades are also used.

Table 13: Six examples of Eye-tracking used to measure visual fatigue

Reference	Eye tracker	Indicators/Features	Device	Tasks	Main results
(Julie Iskander et al., 2019)	Tobii	Vergence angle	HTC Vive	Following cubes at various depths	Vergence angles significantly higher in VR than in the ideal case and higher variability as well
(Jacobs et al., 2019)	Pupil Labs	Blink rate Pupil diameter	HTC Vive Pro	Find and select symbols on two disks	Dynamic camera adjustment (stereoscopy parameters) lead to a higher blink rate and smaller pupil diameter than no camera changes
(Shen et al., 2019)	aSee Pro VR eye tracker	Blink rate	HTC Vive	Watching videos (no precision on type, emotions…)	Blink rate ratio (static group & constant speed group): declining (0–15 min), smooth fluctuation (15–45 min), and rising (45–50 min)
(Y. Wang et al., 2019)	aGIASSDKII (Beijing 7invensun Technology Co., Ltd., China)	Blink rate Fixation Saccades	HTC Vive	Watching video	Increasing fixation, blinking, saccades length over time (4 periods)
(Thai et al., 2020)	Pupil Labs	Blink rate	HTC Vive Pro	Watching video (CGI 3D animated: 5 different)	Decreasing blink rate
(T. Kim & Lee, 2020)	Infrared cameras	Blink rate Pupil accommodation speed Eye-closed duration	Tablet	Watching images	Pupil size control slowdowns Increasing blinking

Table 14 page - 71 -, presents seven experiments that used eye-tracking to study stress. Fixation is the leading used indicator. Studies using eye-tracking to study stress in VR are only beginning.

Table 14: Seven examples of Eye-tracking used to measure stress

Reference	Eye tracker	Indicators/Features	Device	Tasks	Main results
(Herten et al., 2017)	SMI Eye Tracking Glasses 2.0	Fixation	In-person	Trier Social Stress Test	Fixation duration increasing

			(without screen)		
(Macatee et al., 2017)	EyeLink 1000 (SR Research Ltd, Ottawa, Ontario, Canada)	Blink rate Fixation Saccades	PC screen	Image with facial expression, naming number, 2 minutes speech preparation "Why are you a good friend?"	Blinks Fixation Saccades decreasing
(Moacdieh & Sarter, 2017)	Applied Science Laboratories D6 desktop-mounted eye tracker	Gaze movements Fixation Saccades	PC screen	Searching the correct symbol (stressors: Time pressure and reward)	Stress leads to increasing gaze related behaviours
(Simonovic et al., 2018)	Tobii-X2-30	Fixation	PC screen (laptop)	Iowa Gambling Task (decision making)	Fixation and duration of it increase
(Cabrera-Mino et al., 2019)	ETGs (SensoMotoric Instruments [SMI, Teltow, Germany])	Pupil diameter	Physical (without screen)	Manikin-based simulation of a patient with decompensated heart failure	Pupil diameter decreases especially for novices
(Hirt et al., 2020)	Pupil Labs	Pupil diameter	HTC Vive	Shop floor with machine tool on fire, visual and auditory alarm, raising water level to tolerate	Pupil diameter decreases
(Shi et al., 2020)	Tobii	Gaze transition approximate entropy	HTC Vive	Pipe maintenance task (stressful or not)	Vertical gaze movement patterns show quicker and repeated information scan while stressed

Table 15 page - 72 -, presents six experiments that used eye-tracking to study mental workload. Sirois and Brisson (2014) remind us that mental workload or arousal changes are rarely larger than 0.5 mm. Due to fatigue, the average pupil size decreases and fluctuates. The most common indicator used is pupil size (five out of six). Studies using eye-tracking to study mental workload in VR are at an early stage.

Table 15: Six examples of Eye-tracking used to measure mental workload

Reference	Eye tracker	Indicators/Features	Device	Tasks	Main results
(Puma et al., 2018)	EyeLink 1000 remote eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada)	Pupil diameter	PC screen	Priority ManagementTask	Pupil diameter decreases
(Bækgaard et al., 2019)	Pupil Labs	Gaze movements Pupil diameter	HTC Vive	Fitts' law task	Pupil diameter increases
(C. Wu et al., 2019)	Tobii Pro Glasses 2.0	Gaze movements Pupil diameter	Physical tool with screen	Da Vinci Surgical System	Gaze entropy increases

(Buchholz & Kopp, 2020)	Tobii 4C	Fixation Pupil diameter Saccades	PC screen	Monitor the temperature gauges of several machines and increasing or decreasing temperature	Pupil diameter decreases All other parameters stay stable (no significant difference among 3 load difficulty)
(Das et al., 2020)	Tobii Pro Glasses 2.0	Fixation Saccades	Oculus rift	Electric overhead traveling	Fixation frequency increases Saccades' amplitude increases
(Van Acker et al., 2020)	SMI Eye Tracking Glasses	Pupil diameter	Physical (without screen)	Assembly task (decision making and execution)	Pupil diameter stays stable between complex and less complex task

3.4.2.3 ELECTROCARDIOGRAPHY (ECG)

Electrocardiography records myocardial activation from several vantage points on the body's surface, which allows analysis of electrical activation in different myocardial regions (Ganz, 2012; Matos & Pereira, 2012). The signal obtained from this electrical activation is formed of three main components:

- P wave, the depolarization of the atria
- QRS complex, the depolarization of the ventricles
- T wave, the repolarization of the ventricles

Based on those components, several features/indicators can be inferred to measure physiological responses to stimuli (H.-G. Kim et al., 2018; Carneiro et al., 2019; Heard et al., 2019; Hughes et al., 2019; Tao et al., 2019; E. Chang et al., 2020; Vanneste et al., 2020): see Figure 31 page - 73 -.

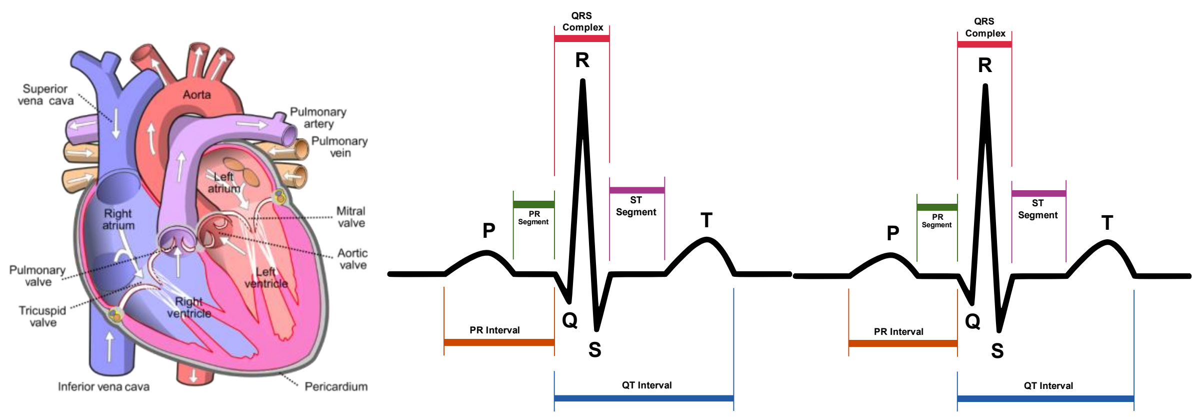


Figure 31: Front view of a heart showing the atria (left) (wapcaplet, s.d.) and ECG signal with labels (right) [1]

High-frequency (HF) variations (0.04–0.15 Hz) in heart rate are considered to be parasympathetically mediated activities. Low-frequency (LF) variations (0.15–0.4 Hz) are considered a product of both parasympathetic and sympathetic activities (Shaffer & Ginsberg, 2017; Wulvik et al., 2020).

[1] Created by Agateller (Anthony Atkielski), converted to svg by atom., Public domain, via Wikimedia Commons

Table 16- 74 - presents seven experiments that used ECG to study cybersickness with VR. RR intervals (time separating two QRS) and Heart rate variability indicators are used to measure cybersickness.

Table 16: Seven examples of ECG used to measure cybersickness

Reference	Sensor	Indicators/Features	Device	Tasks	Main results
(Mark S. Dennison et al., 2016)	Biopac MP150 (BIOPAC Systems, Inc.)	RR intervals Heart rate variation	Oculus Rift	Half-Life 2 game level	RR intervals decrease Heart rate variability increases with HMD compared to PC
(Gavgani et al., 2017)	PowerLab-8s	Heart rate variation	Oculus Rift	Rollercoaster (Helix, Archivision, NL)	Heart rate variation increases 1st and 2nd day but similar to baseline during 3rd day
(Wibirama et al., 2018)	WEB-5500; Nihon KodenCo., Tokyo	Heart rate variability	Stereoscopic PC screen	Watching videos (walking in a city & rollercoaster)	Heart rate variability increases the first three minutes, slightly decreases 3 to 6 minutes, and increases during 6 to 15 minutes
(Garcia-Agundez et al., 2019)	Gtec.at	RR intervals Heart rate variability	Oculus Rift	Controlling a plane	Not clear indicators used to classify and correlate with SSQ (machine learning), but review by authors show an increase in Heart rate variation
(Geršak et al., 2020)	Biopac MP150 (BIOPAC Systems, Inc.)	RR intervals Heart rate variability	Oculus Rift DK1, DK2, CV1, Samsung Gear VR, Samsung Galaxy Note 4, TV	Watching video	RR intervals decrease Heart rate variability increases with HMD and more than with TV
(Takurou Magaki & Vallance, 2020)	Empatica E4	RR intervals Heart rate variability	Oculus Go versus PC	Collecting 5 objects in 3 minutes by walking	VR and PC have different impacts on Heart rate variability
(Niu et al., 2020)	Biopac MP150 (BIOPAC Systems, Inc.)	RR intervals Heart rate variability	Oculus Rift Versus PC screen (models not mentioned but citation to previous paper)	Watching video	HMD RR intervals and Heart rate variability different from PC

Table 17 page - 75 - presents eight experiments used to study stress. RR intervals and Heart rate variability are the most used indicators. Techno-stress has also been measured via ECG (Kalischko et al., 2020).

Table 17: Eight examples of ECG used to measure stress

Reference	Sensor	Indicators/Features	Device	Tasks	Main results
(Ahmaniemi et al., 2017)	Gtec.at	RR intervals Heart rate variability	Samsung Gear VR headset + Galaxy S7	Watching video	Heart rate lower with audio-only compared to full VR
(Heikoop et al., 2017)	PowerLab-8s	RR intervals Heart rate variability	CAVE	Doing nothing or doing what subjects want or counting red cars while in a car driving automatically	Heart rate variability is similar in different conditions RR intervals (extracted sub-indicators) decrease when subjects are doing what they want compared to counting red cars
(Brugnera et al., 2018)	STMicroelectronics	RR intervals Heart rate variability	PC screen	Mental arithmetic challenges, Montreal Imaging Stress Task (MSTI), Stroop Colour-Word and Speech tasks	Respiration rates decrease during verbal stress tasks compared to MSTI Heart rate variability increases with stress
(Barreda-Ángeles et al., 2020)	Biopac MP150 (BIOPAC Systems, Inc.)	RR intervals Heart rate variability	Samsung Gear VR + S6	Performing two-minute speeches to three virtual audiences (positive, neutral, negative) composed of 10 males around their thirties	Heart rate variability increases in front of positive and negative audience
(Bu, 2020)	WEB-1000, NIHON KOHDEN	RR intervals (mRR, SDNN, Distance Poincar´e index)	HTC Vive	Watching videos 1) Relaxation Task: woods and river VR 2) Stress Task: roller coaster 3) Recovery Task: simulated galaxy	Maximum stress at the beginning of stress task,
(Fadeev et al., 2020)	MCScap	HR RMSSD lnLF lnHF	HTC Vive	1)Richie's Plank Experience 2)Epic Roller Coasters 3)Nature 4)Treks VR 5)Home—A VR Spacewalk	Heart rate variability decreases, suggesting a decrease in parasympathetic activity in the most stressful condition: Home—A VR Spacewalk
(Kerous et al., 2020)	Psychlab	HR HRV (RMSSD)	HTC Vive	Park 1, Social, Stroop, Social Stroop, Park 2	Heart rate variability increases with stressors

					(Social, Social Stroop)
(Rodrigues et al., 2020)	Biopac Bionomadix	RR intervals HR Heart rate variability (RMSSD, SDNN, HRVTi)	HTC Vive	Exploring Scenario 1: Empty room Scenario 2: Elevated alley Scenario 3: Persistent threat	Indicators increase with stress (scenario 3) but decrease over time

Table 18 page - 76 - presents eight experiments using ECG to study mental workload. RR intervals and Heart rate variability (and sub-indicators) are the most used indicators.

Table 18: Eight examples of ECG used to measure mental workload

Reference	Sensor	Indicators/Features	Device	Tasks	Main results
(Ahonen et al., 2018)	Faros eMotion 180°	RR intervals (IBI) HR HRV SDNN	PC screen	6 programming tasks in collaboration. Pairs of subjects switching roles every 7 minutes (active programming using keyboard and mouse, or guiding and commenting)	Failure outcomes are significantly more arousing for guiding role than active programming role
(Jeong et al., 2018)	Biopac MP-100	Heart rate (HR)	SKUD 3 simulator	Driving comparison of joystick versus steering wheel interaction	Driver workload and fatigue were lower (HR) under joystick driving compared to steering wheel driving
(Chanel et al., 2019)	Faros eMotion 360°	RR intervals (SD) HRV	PC screen	Reproducing sequences of alphabet characters, Mental arithmetic problem	RR intervals increase, HRV decreases with difficulty
(Mansikka et al., 2019)	Nexus-10 MKII	HR decreased interbeat-interval (IBI)	CAVE	Tactical goal awareness in a flight simulator (Finnish Air Force F/A-18C/D), commit and approach tasks	High demand task had a higher workload than lower demand, and IBI decreases
(Reinerman-Jones et al., 2019)	Advanced Brain Monitoring System B-Alert X10	HR IBI HRV	PC screen (mouse or touch screen input)	Emergency operating procedure for Loss of All Alternating Current in Nuclear Power Plant Simulator: Analog (16 checkings, 5 detections, and 9 response tasks) versus Digital ((8 checkings, 8 detections, and 8 response implementation)	Heart rate increases with high workload

(Jafari et al., 2020)	Holter-ECG (Beneware CT-08 model)	RR intervals (SDNN, SDNNIDX, pNN50, RMSSD) HR HRV (LF/HF)	Corys Metro Train Simulator (physical commands with screens)	Subway train operation simulator (routine operations versus nonroutine operations)	Nonroutine operations lead to significant different indicators behaviour: HR increases, Mean RR decreases, SDNN, SDNNIDX, pNN50, RMSSD decreases, LF/HF increases
(Wulvik et al., 2020)	Shimmer3 ECG	HR HRV	PC screen	Control room task of ship bridge simulator (open sea scenario versus harbour scenario)	HRV increases more in harbour scenario Strongest correlations to mental state were peak frequency in HF HRV
(S. Yang et al., 2021)		HR HRV		Driving simulation (baseline, N-back, texting, and N-back + texting distraction)	HR and HRV differ depending on mental workload

3.4.2.4 ELECTRODERMAL ACTIVITY (EDA)

Electrodermal activity (EDA) comprises the changes in electrical conductance of an applied current provoked by the skin sweat gland activity modulation (Posada-Quintero & Chon, 2020). Glands located on the hands' plantar and palmar sides are responsive to psychological stimuli (rather than to thermal stimuli) and sympathetic neural activity (Critchley & Nagai, 2013). According to Posada-Quintero and Chon, EDA represents a quantitative functional measure of sudomotor activity, therefore, an objective assessment of arousal. EDA can be used to evaluate the autonomic function and assess levels of cognitive arousal. Two types of indicators can be inferred from EDA signal Phasic Skin Conductance Response (SCR), Tonic Skin Conductance Level (SCL) (Boucsein, 2012; Boucsein et al., 2012; Dawson et al., 2016): Figure 32 page - 78 -, to visualize those indicators. Like other sensors, EDA is sensitive to temperature and humidity(Bari et al., 2018).

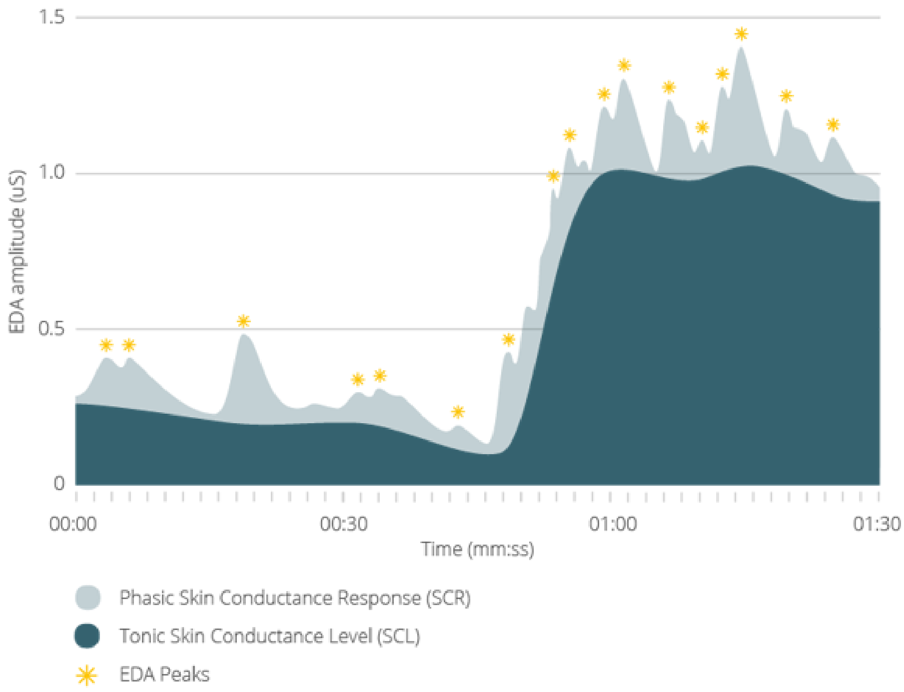


Figure 32: EDA signal with Phasic Skin Conductance Response (SCR), Tonic Skin Conductance Level (SCL), and Peaks © Bryn Farnsworth – Imotions (imotion, s.d.)

Table 19 page - 78 - presents seven experiments that used EDA to study cybersickness in VR. SCR sub-indicators are usually used, but some studies are not clear about which indicator they rely on. EDA is described as not being a reliable way to accurately measure motion sickness (Smyth et al., 2021).

Table 19: Seven examples of EDA used to measure cybersickness

Reference	Sensor	Indicators	Device	Tasks	Main results
(Mark S. Dennison et al., 2016)	Biopac MP150 (BIOPAC Systems, Inc.)	SCR?	Oculus Rift	Half-Life 2 game level	skin conductivity increases compared to the initial rest period
(Gavgani et al., 2017)	UFI Model 2701 BioDerm Skin Conductance Meter (UFI, Morro Bay, USA)	SCR SCL	Oculus Rift	Rollercoaster (Helix, Archivision, NL)	Finger SCL increases: on the 1st min of the ride, on the 1st day, it raises by+9.2±2.5 µS. It increases towards the end of the ride. An increase in tonic finger SCL decreases on the 2nd and 3rd day (+5.5 ± 1.3 and 4.4 ± 1.4 µS). Phasic finger SCL is variable. SCL of the forehead is associated with nausea symptoms
(Plouzeau et al., 2018)	E4 Empatica wristband	SCR?	Oculus Rift CV1	Joystick navigation in a virtual forest with a gravel path (adjust the	SCR decreases with adapted acceleration adjusted to EDA signal

				navigation accelerations)	
(Garcia-Agundez et al., 2019)	Gtec.at g.GSRsensor	SCR?	Oculus Rift	Controlling a plane	Not clear, classify several signals with ML in correlation to SSQ
(Geršak et al., 2020)	Biopac MP150 (BIOPAC Systems, Inc.)	SCR	Oculus Rift DK1, DK2, CV1, Samsung Gear VR, Samsung Galaxy Note 4, TV	Watching video	SCR pulses increases in VR
(Takurou Magaki & Vallance, 2020)	Empatica E4	SCR width Peak EDA	Oculus Go versus PC	Collecting 5 objects in 3 minutes by walking	SCR width higher and more EDA peaks in VR compared to PC
(Niu et al., 2020)	Biopac MP150 (BIOPAC Systems, Inc.)	SCR (peak number, amplitude, slope, and rise time)	Oculus Rift Versus PC screen (models not mentioned but citation of previous paper)	Watching video	Number of peaks, amplitude, and slope are higher in VR than PC

Table 20- 79 - presents six experiments using EDA to study stress. Both SCL and SCR (and sub-indicators) are used to assess stress in VR. Stressors increase electrodermal activity.

Table 20: Eight examples of EDA used to measure stress

Reference	Sensor	Indicators	Device	Tasks	Main results
(Ahmaniemi et al., 2017)	Gtec.at	SCL	Samsung Gear VR headset + Galaxy S7	Watching video	SCL lower in Audio only condition
(Barreda-Ángeles et al., 2020)	Biopac MP150 (BIOPAC Systems, Inc.)	SCL SCR	Samsung Gear VR + S6	Performing two-minute speeches to three virtual audiences (positive, neutral, negative) composed of 10 males around their thirties	SRC increases in front of a negative audience
(Caldas et al., 2020)	Biosignals Plux Explorer research kit	µSCL maxSCL minSCL nSCR	Oculus rift	Skydiving game (passing through colored rings before landing)	SCL increases with a higher challenge which could be due to stress or fear
(Fadeev et al., 2020)	MCScap	Fluctuations = Peak EDA?	HTC Vive	1)Richie's Plank Experience 2)Epic Roller Coasters 3)Nature 4)Treks VR 5)Home—A VR Spacewalk	Roller Coasters with the most fluctuations

(Kerous et al., 2020)	Psychlab	non-specific skin conductance responses (nSCR) Tonic EDA (CDA Tonic)	HTC Vive	Park 1, Social, Stroop, Social Stroop, Park 2	nSCR and CDA Tonic increase with stressors (Social, Social Stroop)
(Krogmeier & Mousas, 2020)	Shimmer3 GSR+ sensor	Peak EDA	HTC Vive Pro Eye	Incarnating different avatars in front of a mirror or not	Zombie as self-avatars show an increase in Peak EDA compared to a mannequin which can be provoked by stress or anxiety

Table 21 page - 80 - presents five experiments that used EDA to study mental workload. Both SCL and SCR are used to assess mental workload, but sub-indicators are not always described. Mental workload seems to increase electrodermal activity both in phasic and tonic components.

Table 21: Five examples of EDA used to measure mental workload

Reference	Sensor	Indicators	Device	Tasks	Main results
(Ahonen et al., 2018)	Shimmer 3+ GSR	SCL SCR	PC screen	6 programming tasks in collaboration. Pairs of subjects switching roles every 7 minutes (active programming using keyboard and mouse, or guiding and commenting)	Failure outcomes are significantly more arousing for guiding role than active programming role
(Jeong et al., 2018)	Biopac MP-100	Not clear	SKUD 3 simulator	Driving comparison of joystick versus steering wheel interaction	Driver workload and fatigue were lower under joystick driving compared to steering wheel driving
(Luong et al., 2019)	Shimmer3 GSR+	SCL	HTC Vive	N back tasks - 3 levels of difficulty	Natural Walking drive (secondary task) to higher mental workload (SCL increases) while performing the task
(Gupta et al., 2020)	Shimmer GSR+	Mean Frequency Peak Frequency Total Power	HTC Vive	N back tasks – 2 levels of difficulty, with or without the help of a virtual agent	No relationship between trust (to a virtual agent) and cognitive load Mean and peak frequency show an effect of virtual agent accuracy
(Wulvik et al., 2020)	Shimmer3 GSR +	TOTpow LF_HF_ratio	PC screen	Control room task of ship bridge simulator	EDA features increase with

	nSCR SCR AmpSum SCR SCR PhasicMax SCL Raw Mean SC	(open sea scenario versus harbour scenario)	increasing levels of workload and stress

The previous sections have presented different methods of objective measuring of VR side effects. The following section will review subjective methods. Overview and conclusions about thses methods are presented in the section 3.4.2.6 page - 83 -.

3.4.2.5 SUBJECTIVE CYBERSICKNESS, VISUAL FATIGUE, STRESS, AND MENTAL WORKLOAD

The Simulator Sickness Questionnaire (SSQ) has been used widely with VR, yet other questionnaires appear more relevant (Sevinc & Berkman, 2020; Stanney, Lawson, et al., 2020; Cid et al., 2021; Somrak et al., 2021). Several co-existing questionnaires have been developed directly for VR:

- Cyber Sickness Questionnaire (CSQ) by Stone III (2017)
- Virtual Reality Symptoms Questionnaire (VRSQ) by Ames et al. (Ames et al., 2005)
- Virtual Reality Sickness Questionnaire (also shorten VRSQ) by H. K. Kim et al. (2018)
- Virtual Reality Neuroscience Questionnaire (VRNQ) by Kourtesis et al. (2019)

Since we are both interested in cybersickness and visual fatigue, we need to use a questionnaire that combines oculomotor-related symptoms and motion sickness-related symptoms. Therefore, the Virtual Reality Sickness Questionnaire (VRSQ) by H. K. Kim et al. (2018) seems the most appropriate for our purposes: see Table 22- 81 -. Previous works used the Virtual Reality Sickness Questionnaire : (Caldas et al., 2020; Porcino et al., 2020).

Table 22: VRSQ by H. K. Kim et al. (2018)

ID	Statement	Choices			
		None (0)	*Slight (1)*	*Moderate (2)*	*Severe (3)*
VRSQ_1	General discomfort	O	O	O	O
VRSQ_2	Fatigue	O	O	O	O
VRSQ_3	Eyestrain	O	O	O	O
VRSQ_4	Difficulty concentrating	O	O	O	O
VRSQ_5	Headache	O	O	O	O
VRSQ_6	« Fullness of the head »	O	O	O	O
VRSQ_7	Blurred vision	O	O	O	O
VRSQ_8	Dizziness with eye closed	O	O	O	O
VRSQ_9	Vertigo*	O	O	O	O

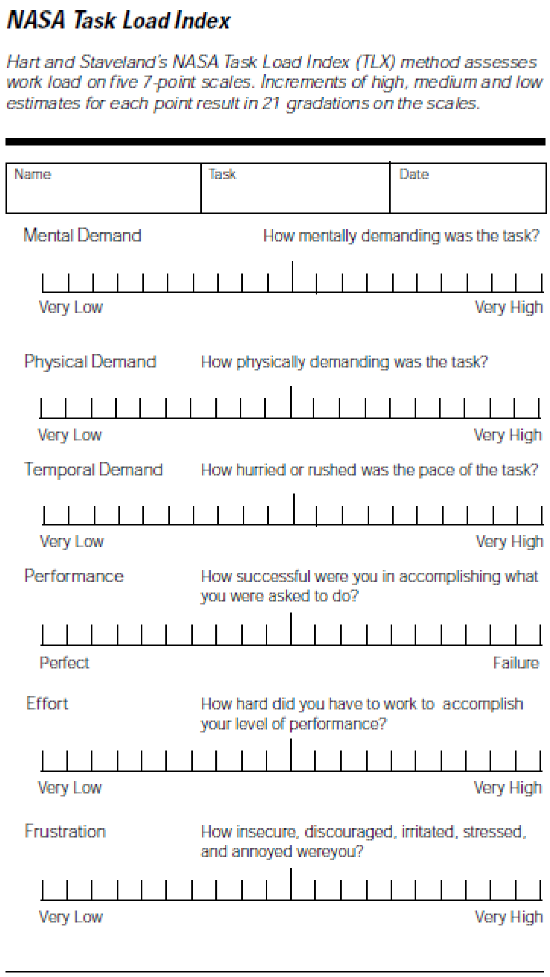
**(loss of orientation with respect to vertical upright)*

Several questionnaires exist to measure stress. The State-Trait Anxiety Inventory (STAI) by Spielberger et al. (1983) is widely used. We want to measure stress related to a task which has just completed, and the standard version has too many items. Therefore, the STAI-6 by Marteau and Bekker (1992) seems adequate for this purpose: see Table 23 page - 82 -.

Table 23: STAI-6 by Marteau and Bekker (1992)

ID	Statement	Choices			
		Not at all	*Somewhat*	*Moderately*	*Very much*
STAI-6_1	I feel calm	O	O	O	O
STAI-6_2	I am tense	O	O	O	O
STAI-6_3	I feel upset	O	O	O	O
STAI-6_4	I am relaxed	O	O	O	O
STAI-6_5	I feel content	O	O	O	O
STAI-6_6	I am worried	O	O	O	O

According to Paxion et al. (2014), NASA Task Load indeX (Hart & Staveland, 1988) presents more advantages than others based on seven criteria: sensitivity, diagnosticity, selectivity/validity, intrusiveness, reliability, implementation requirements. Still, it needs to be used according to its specific focus dimensions: see Figure 33 page - 82 -. Mental workload questionnaires such as the NASA-TLX measures distinct constructs even if a total unidimensional score is possible (Matthews et al., 2020)


NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure 33: NASA-TLX by Hart & Staveland (1988)

3.4.2.6 SUMMARY OF MEASURING VR SIDE EFFECTS, ACUTE STRESS AND MENTAL OVERLOAD

Eye-tracking, ECG, and EDA seem reliable psychophysiological sensors to measure cybersickness, visual fatigue, stress, and mental workload (Cholach & Lebid, 2019). Few studies use ECG and EDA to measure visual fatigue, although some exist (Ramadan & Alhaag, 2018). However, indicators inferred from the signals of those sensors show various trends: increasing, sometimes decreasing in contradiction with what could be expected. A growing body of studies combines several sensors. Other studies also use other sensors or indicators: e. g. entropy controllers' movements to measure mental workload (Reinhardt et al., 2019). More and more experiments use eye-tracking, ECG, and EDA simultaneously. Also, using questionnaires to allow correlations between subjective state and physiological recording is necessary. A ready-for-use monitoring toolkit to measure VR side effects, acute stress, and mental overload does not currently exist (Epps, 2018). The reliability of such a monitoring toolkit should also be tested in a simple virtual environment before being applied to complex environments like working in VR. Since physiological signals can create a large amount of data and detection needs to be done with confidence, Machine Learning techniques (Epps, 2018; Rebala et al., 2019; Debie et al., 2021) are used to identify which indicators inferred from signals are the best to measure each state. Despite those issues, using physiology to assess ergonomics risks of VR is promising. But as demonstrated in the following sections, all those states seem tangled, and distinguishing each of them appears challenging. Techniques like Electroencephalography (EEG) or functional near-infrared spectroscopy (fNIRS) have been used in VR to measure brain activity to assess cybersickness, visual fatigue, stress, and mental workload. However, material cost and noise due to worn HMD are still obstacles for getting a clear signal, even if improvements are onon their way for easier use.

3.5 TANGLE OF VR SIDE EFFECTS

3.5.1 TANGLES BETWEEN VR SIDE EFFECTS, STRESS, AND MENTAL OVERLOAD

3.5.1.1 INTRODUCTION

Cybersickness, visual fatigue, acute stress, and mental workload are complex. They are usually investigated one by one. However, a growing body of research is trying to understand the tangles between all of them better. It is critical, since working in VR requires the use of various perceptions, cognitions, and actions. This section describes three tangles: between stress and cognition, visual fatigue/cybersickness and mental workload, and cybersickness and stress.

3.5.1.2 STRESS AND COGNITION (EXECUTIVE FUNCTIONS)

The experimental results regarding the effects of stress on cognition are mixed, partly due to tremendous variations in paradigms and methodological quality (Rodeback et al., 2020; Shields, 2020). Most results indicate an impact of stress on cognition that impairs task performances (Anton et al., 2021; Grantcharov et al., 2019). Some other results point to no effects and even positive effects (Martens et al., 2019; Qi & Gao, 2020). The impact of stress on cognition seems to depend on stressor intensity in relation to the task (intrinsic or extrinsic), which can lead to milder acute stress to improve cognitive functions (e.g., decision making, concentration) (Degroote et al., 2020; Kan et al., 2020; Sandi, 2013). To summarize, stress is perceived as a threat or a challenge that impacts cognition differently (Shields, 2020). Research on stress impact cognition concentrates heavily on memory and working memory and call for openings on other cognitive functions (Domes & Frings, 2020).

As mentioned before, acute stress reduces selective attention (Bater & Jordan, 2020; Peter A. Hancock & Matthews, 2015; LeBlanc, 2009; K. Lee & Choo, 2013), enhances memory consolidation (Hidalgo et al., 2019;

Roesler & McGaugh, 2019), and impairs memory recall/retrieval (Klier et al., 2020; Staresina & Wimber, 2019). Stress can also impact executive functions (Gabrys et al., 2019; Oken et al., 2015) like cognitive inhibition and inhibitory control. Executive functions is an umbrella term for cognitive processes such as planning, working memory, attention, inhibition, self-monitoring, self-regulation, and initiation carried out by prefrontal areas of the frontal lobes (Diamond, 2013; S. Goldstein et al., 2014; Sira & Mateer, 2014; Suchy, 2009). But results are also contradictory on whether there are positive (J. Chang et al., 2020; Dierolf et al., 2018) or negative (Johnsen et al., 2012; Roos et al., 2017; Shields, Doty, et al., 2017; Shields, Sazma, et al., 2017) impacts on executive functions. However, a meta-analysis (Shields et al., 2016) concluded that stress impaired working memory and cognitive flexibility, have subtle effects on inhibition. According to Mandrick et al. (2016), contradictory effects of stress on cognitive performance can be explained by the fact that it may be protected under stress thanks to compensatory efforts (cognitive strategies to maintain task efficiency), which has a psychophysiological cost. This can be supported by experimental results (Dierolf et al., 2017; C. Jiang & Rau, 2017; Möschl et al., 2017; Qi et al., 2018). As reminded by Y. Kim et al. (2017), depending on the paradigm, the induced stress may be too low to impair the performance, and/or the task may be too easy for stress to have an effect. Depending on task load, stress can impact different cognitive performances (see Figure 34 page - 84 -): the higher working memory resources required by a task, the higher the impact of stress on cognitive performances (Plieger & Reuter, 2020).

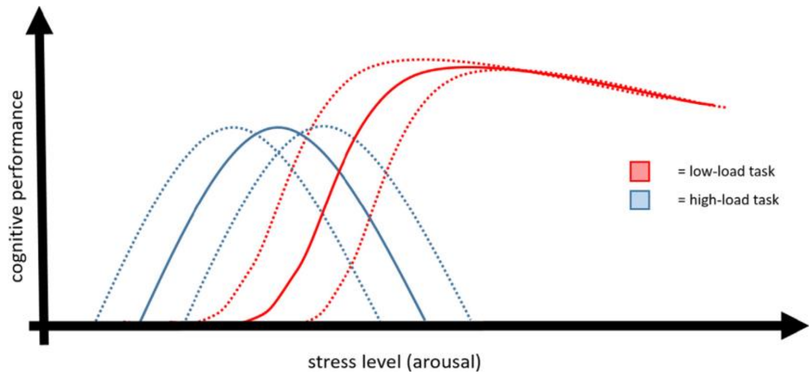


Figure 34: The association between stress level and cognitive performance dependent on cognitive load (red: low load task; blue: high load task) and the influence of additional moderating effects (dotted lines; e.g., individual characteristics), Plieger and Reuter (2020).

Following their experiment on breakfast privation and noise (85 dB) impacts (stressors) on cognitive performance during a 2-back task, Bottenheft et al. (2020) propose an update of the hypothetical relation between task demands, performance, workload, and effort from Veltman et al. (2003). Bottenheft et al. study indicates that individuals spent extra effort to maintain task performance in the presence of noise. Although this model proposal (see Figure 35 page - 85 -) cannot be generalized in every cognitively demanding task, it shows the possible tangle between stress and mental workload.

In HCI, connections between mental workload and stress have been raised by Alsuraykh et al. (2019) following several experiments. Experimental proofs show that anxiety and stress before a task impact measures (with functional Near-Infrared Spectroscopy) of mental workload (Alsuraykh et al., 2018). Vice versa, mental overload can concur to stress or emotional changes (Gabana et al., 2017; Epps, 2018; Truschzinski et al., 2018).

The tangle between stress and mental workload is an issue that requires more research. That information is of interest for the INFINITY project as if users cannot fully operate their cognitive resources due to stress, tasks, and work performances could be impacted negatively.

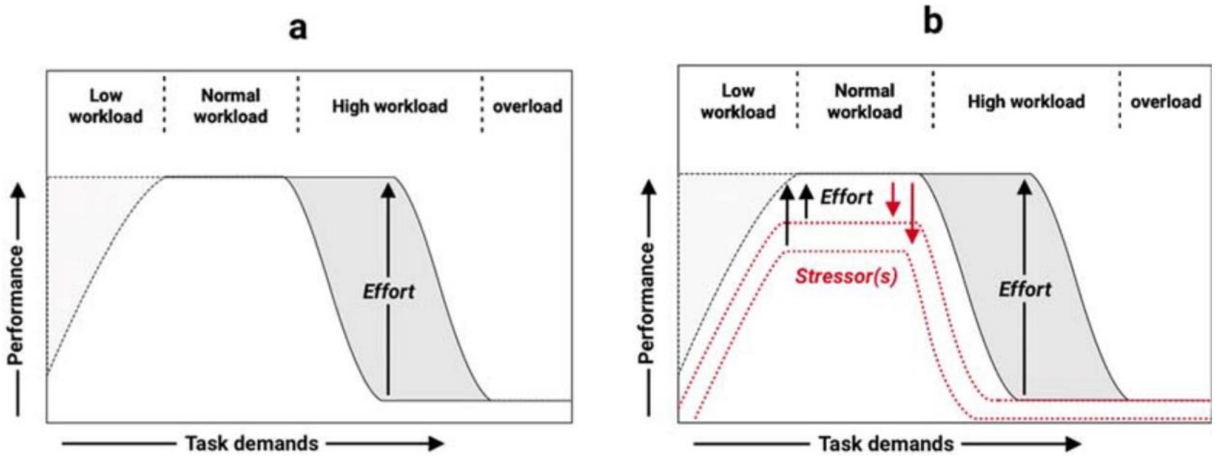


Figure 35: Update proposal of the hypothetical relation between task demands, performance, workload, and effort. a Original model by Veltman et al. (2003), b update by Bottenheft et al. (2020)

3.5.1.3 VISUAL FATIGUE, CYBERSICKNESS, AND MENTAL WORKLOAD

General fatigue while working on a computer affects the visual system due to several cognitively demanding tasks (Marandi et al., 2018). Completing tasks which induce visual stress seems to impact cognition while causing visual fatigue based on brain activities (D. Kim et al., 2011; Leigh & Zee, 2015; Kweon et al., 2018). As Huckauf and Eberhardt (2019) analysed, visual stress and strain induced by stereoscopic environments' inhibitory process of information at all depths require vast amounts of working memory resources. The higher level of cognitive processing can be seen as a positive effect of stereoscopy when tasks consist of object depth discrimination. But when such mental workload is combined with complex cognitive tasks such as learning or working, this should be considered a risk.

Repeated activation (Cai et al., 2017) or maintained activation (C. Chen et al., 2017) of stereopsis by stereoscopic images inducing sensory-motor conflicts could cause visual fatigue. In both cases, it implies that visual perception with sensory-motor conflicts requires more effort to process those images for our brain. The task of processing images with impaired cues is difficult (Eckstein et al., 2017). It requires more working memory resources. Therefore, visual fatigue caused by S3D is at least correlated with cognitive fatigue (Mun et al., 2012). Thus, visual fatigue and cognitive fatigue seem linked. Iskander *et al.* (2018) further state that visual fatigue is more related to mental than muscular fatigue. This would mean that visual fatigue is a reaction to mental overload induced by processing stereoscopic images with cue impairments. S. Chen and Epps (2014) are testing this perception-related cognitive load hypothesis. However, their results do not allow a generalization of a crosslink between visual fatigue and cognitive load. The mental workload seems to affect the early stages of visual processing. Hence, higher cognitive function and early perceptual processing may not be as independent as usually presented (P. Liu et al., 2018).

Sangin Park *et al.* (Park et al., 2015) indicate that links between visual fatigue and mental workload imply that visual fatigue can be included in cognitive load theory. If we refer to Sweller (2011), extrinsic load (i.e., dependent on how information is presented and acquired) could predict such an effect. Sensorimotor impairments such as vergence-accommodation conflict could be considered extrinsic loads that induce additional load on the working memory (Baddeley, 2010). Vergence-accommodation conflict can interplay with mental workload (Daniel & Kapoula, 2019). Therefore, repeated conflicts might saturate working memory resources (Bernhardt & Poltavski, 2021). Thus, visual fatigue would be a strategic response of our brain to cope with extra load induced by sensorimotor conflicts to process visual information. Abnormal or unexpected bodily signals seem to attract more processing resources (Critchley & Garfinkel, 2018). Furthermore, cybersickness seems to impair performance, like reaction time (Mittelstaedt et al., 2019). It indicates an impact of sensorimotor conflicts on cognition. This impact on performance can also be seen with vergence-accommodation conflict (Alhusuny et al., 2020). Conversely, mental effort also seems to impact visual functions (Hynes et al., 2018; Vera et al., 2017).

On top of its negative symptoms, visual fatigue could also burden workers' available working memory resources. Less information is available for cybersickness. But since it is also due to sensorimotor conflicts, the same prediction could be expected. Therefore, studying links between visual fatigue/cybersickness and mental workload and on alleviating the possible effect of visual fatigue on mental workload is necessary for INFINITY.

3.5.1.4 CYBERSICKNESS AND STRESS

The possible tangles between cybersickness and stress are not frequently investigated in the literature. However, both cybersickness and stress use similar psychophysiological measures and stimuli but for different effects. For instance, previous studies would identify cybersickness (Mark S. Dennison et al., 2016; Gavgani et al., 2017; Wibirama et al., 2018) during a rollercoaster task, while others identify stress (Bu, 2020; Fadeev et al., 2020). According to Pot-Kolder et al. (2018), anxiety mediates cybersickness symptoms (nausea and disorientation). Pot-Kolder et al. indicate, based on their study, that reported anxiety symptoms may partially reflect cybersickness symptoms and vice versa. However, very few contributions in the field of VR (or related issues) make reference to this possible tangle at this point. A systematic review of individual predictors of the susceptibility for motion-related sickness by Mittelstaedt (2020) acknowledges this possible interplay between cybersickness and stress while reviewing studies using salivary secretions. Mittelstaedt calls for more studies to determine if the increased sympathetic tone results from acute or chronic stress triggered by increased physical activity and if stress is also affecting motion sickness susceptibility.

It is not yet clear if we can talk about a link between cybersickness and stress. However, some results tend to suggest such a link is worth exploring as it could help reduce both effects whilst working in VR in INFINITY.

3.5.1.5 SUMMARY OF TANGLES BETWEEN VR SIDE EFFECTS, STRESS, AND MENTAL OVERLOAD

Cybersickness, visual fatigue, stress, and mental overload are complex constructs. Research is still required to understand those states better. Bringing people into VR, e. g., to work, requires us to consider all of them to influence user well-being and performance. Often treated as isolated states, it seems that cybersickness, visual fatigue, stress, and mental overload could have some tangles. Therefore, they could influence one another. This has been identified for stress and cognition, visual fatigue/cybersickness, mental workload, and cybersickness and stress. This shows that immersing humans, in our case police workers, is not anodyne and could affect several psychophysiological aspects. This means that by aiming to prevent cybersickness, visual fatigue, stress, or mental overload, we may well generate non-desired effects on each state, leading to counterproductive interventions. Such possible tangles also raise an issue on what we measure while assessing those states with physiological sensors and questionnaires. As depicted in section 3.4.2 page - 69 - the same physiological sensors and indicators sometimes show similar results for different states.

3.5.2 ISSUES AT DISTINGUISHING VR SIDE EFFECTS, STRESS AND MENTAL OVERLOAD

3.5.2.1 INTRODUCTION

A significant issue of human response to VR is the ability to encompass a variety of complex psycho-physiological variations all depending on numerous components (Krohn et al., 2020; Michela et al., 2019): hardware characteristics (IPD range for lenses, headset size, and weight, FOV, image quality…), sensorimotor inputs/outputs (haptic, sound…), software characteristics (stereoscopic disparity, colours, movements), type of interactions with the virtual environment, content characteristics (what tasks users have to fulfil, emotions induced), trait and users' relation to each of these components. As demonstrated in the following section, tangles between states could influence measures. Therefore, the validity of the in-lab strategy to reproduce such complexity in control settings is challenging (Holleman et al., 2020; Vasser & Aru, 2020). Here, we address this issue by describing how physiological measures and questionnaires are usually performed by inhibiting possible confounding effects of VR stimuli. Namely, stress, cybersickness, and mental workload inducing behaviour and physiological variations related to the cognitive process are aligned with such measures or biased by other components of the experimental setup. We also indicate that physiological variables usually used to assess cybersickness, visual fatigue, stress, and mental workload cannot be clearly assigned to one state at a deeper level.

3.5.2.2 CONFOUNDING EFFECTS RELATED TO STIMULI ADMINISTRATION OPERATED MEASURES AND EXPERIMENTAL METHODS

A well-documented issue with studies relying on physiological data is confounding effects: one state influencing another, making it impossible to differentiate one state from another, and various data processing for hypothesis testing; whether data is acquired with eye-tracking, ECG, or EDA (Dirican & Göktürk, 2011; Sirois & Brisson, 2014; Shaffer & Ginsberg, 2017; Clay et al., 2019; Hughes et al., 2019; Lohani et al., 2019; Tao et al., 2019; Abdelall et al., 2020; Wulvik et al., 2020; Czerniak et al., 2021; Giorgi et al., 2021). Peers sometimes underline the complexity of those states (Argyle et al., 2021). Such issues apply when VR is used to study human psychophysiology or VR itself. For instance, depending on the perceptual channels stimulated (Marucci et al., 2021), whether one sensor is also used to interact with the virtual environment (Silva et al., 2019), 3D object characteristics (depth) (J. Iskander et al., 2019). There is a risk that a specific focus leads to minimising or not considering confounding effects or that one state can be linked to another (P. A. Hancock, 2017; Howards, 2018; Jager et al., 2020). Typically, research focusing on stress and mental workload would emit possible impacts of cybersickness during their physiological data recording. Conversely, researchers focusing on cybersickness would not consider stress or mental workload induced by tasks during their physiological data recording. Relying on one concept at a time also virtually describes a unidimensional psychophysiological state by emitting others that can also explain measure variations.

By extension, contributions regarding human physiological variations when exposed to VR often rely on subjective self-reporting correlation with objective data (E. Chang et al., 2020). Yet, questionnaires are not all standardized. Furthermore, questionnaires are subject to numerous biases (Palaniappan & Kum, 2019). Asking a set of questions before content exposure in Human-Computer Interactions can induce a priming or anchoring effect (Furnham & Boo, 2011; Weingarten et al., 2016; Doherty & Doherty, 2018). Such priming could even influence experimenters (Doyen et al., 2012). In other words, a set of questions can influence participants' self-reporting. Cybersickness specifically implies users are experiencing (and expecting) side effects. Therefore, the complex role of placebo and nocebo effects could even step in, depending on users' traits and emotions relating to the VR experience documented in medicine (Faasse et al., 2019; Geers et al., 2020). Techno-stress, which exists with other devices (La Torre et al., 2019) than HMDs, could also be considered to have a confounding effect. Finally, depending on the task and the cognitive resources it activates, evidence measured (e.g., behavioral data) when comparing condition tasks can reflect other processes than the ones that were measured (Gilbert et al., 2012).

We need to embrace that complexity when measuring human psychophysiological variations within VR (Sirois & Brisson, 2014). This implies robust experimental design and statistics (Jones et al., 2003; Sullivan & Feinn, 2012; Hinkelmann, 2015; Dean et al., 2017). Currently, measuring cybersickness, stress, and mental workload via physiological instruments is debated among peers for their reliability and precision and their opportunity to assess those states better (Ayres, 2020; Crosswell & Lockwood, 2020; Saredakis et al., 2020). Aiming to measure physiological variations due to VR-induced side effects, stress, and mental workload faces the same replication issues faced by science in general and specifically psychology and computer science (Collaboration, 2015; Muthukrishna & Henrich, 2019; Cockburn et al., 2020).

If we refocus on possible connections between different states, HCI research already suggested a connection between stress and mental workload (Alsuraykh et al., 2019). Thus, the issue of making sure of what is measured via physiological sensors is known. In our applied case, this is an issue since we aim to measure several states' live while using VR with such sensors. The ability to distinguish those states or explain their effects on physiological features by peers relies on fundamental neurophysiological processes of humans.

3.5.2.3 IT IS ALL ABOUT THE AUTONOMIC NERVOUS SYSTEM

When explaining how psychophysiological measures reveal whether cybersickness, visual fatigue, acute stress, or mental workload, previous contributions usually relate to the arousal concept and specifically to the Autonomic Nervous System (ANS) reaction: see Figure 24 page - 56 -. As defined in section 3.3 page - 53 -, according to Cohen (2011), arousal: "*refers to the tonic state of cortical activity elicited by subcortical reticular formation that results in increased wakefulness, alertness, muscle tone, and autonomic response (e.g., heart rate and respiration*)." ANS also adapts the organism to internal and external changes, maintaining bodily homeostasis and coordinating bodily responses (Johnson, 2018; Richter & Wright, 2013a). Here is a collection of quotes from previous works that all fundamentally rely on ANS to explain physiological variations. It should be noted that this is just for illustrative purposes, numerous other works do indicate higher ANS activations (than control condition or baseline) for cybersickness, visual fatigue, stress, and mental overload:

Cybersickness

"*Changes in stomach activity, blinking behaviour, and breathing suggest that the mismatch between signals from the real and virtual worlds activate the autonomic nervous system as a response to an uncomfortable situation*." (Mark S. Dennison et al., 2016)

Visual fatigue

"*The pupillary dynamics are governed by the autonomic nervous system and reflect mental activity. As such, they may indicate visual discomfort*." (M. Lambooij et al., 2009).

Mental workload

"*Physiological measures stand on the assumption that as mental workload levels change, there will be a corresponding response in the autonomic nervous system which can be reflected and measured in a number of physiological parameters*" (Midha et al., 2021).

"*Higher mental effort, or workload, is related to a decrease of the parasympathetic activity of the autonomic nervous system, which can be viewed as the "rest and recovery" system and an increase in sympathetic activity, or the "fight or flight" system*." (Bottenheft et al., 2020).

It appears that cybersickness, visual fatigue, and mental workload are fundamentally described as stress responses since they trigger physiological changes governed by ANS. This description is correct as ANS adapts the organism to internal and external changes, maintaining bodily homeostasis and coordinating bodily responses (Richter & Wright, 2013a; Johnson, 2018). Considering those states as stressors is conceptually sound. However, it can be confusing to rely on such a broad concept to explain cybersickness, visual fatigue, and mental workload, especially if we want to distinguish each state, including acute stress (here a negative emotion, see section 3.3 page - 53 -). Relying on describing the activity of the ANS is not enough. We should be able to classify whether the activity is from the sympathetic nervous system (SNS) (Richter & Wright, 2013c) or the parasympathetic nervous system (PNS) (Richter & Wright, 2013b). Otherwise, each state could be seen as confounding while performing physiological measures.

Furthermore, current knowledge does not identify physiological variations due to one state while they could all be at stake. Typically, when using VR, cybersickness will not solely arise. We can expect visual fatigue or stress or mental overload, and even muscle fatigue. Thanks to machine learning techniques, it could be possible to distinguish each state based on physiological measures (Gabana et al., 2017; Epps, 2018; Parent et al., 2019). Of course, brain activity would allow a step further into detection precision. However, as mentioned earlier, it has a high cost, and since workers are wearing an HMD, too many artifacts could jeopardize a precise measure (G. Kim et al., 2018). Ultimately, neural pathways of cybersickness, visual fatigue, or mental workload are still under research. Until studies can distinguish physiological variations induced by each state, it will be difficult to rely on fundamental neurophysiological causes that are precise enough. Each state might happen to be "artifacts" creating noise in the desired state measure. Finally, having workers wearing sensors on their heads might be challenging to realize.

3.5.2.4 MENTION OF PROBABLE CONFOUNDING EFFECTS IN DIFFERENT ASSESSED STATES WITH VR

Reading the discussion and limitation sections of several papers, whether they intend to measure cybersickness, visual fatigue, acute stress, or mental workload there are references to confounding effects being found. Here we collected a sample to provide an overview of contributions pointing to confounding effects of one state on another:

- Visual fatigue or cybersickness in VR as confounding effects of stress assessment (C.-P. Yu et al., 2018; Y. Liu et al., 2019)
- Stress or emotions or general arousal as confounding effects of cybersickness assessment (Mark S. Dennison et al., 2016; Gavgani et al., 2017; Takurou Magaki & Vallance, 2017; T. Magaki & Vallance, 2019; Mittelstaedt, 2020)
- Stress or arousal as confounding effects of mental workload assessment (Galy et al., 2012; Epps, 2018; Collins et al., 2019; Parent et al., 2019; Borghini et al., 2020; Wulvik et al., 2020)
- Visual fatigue or cybersickness as confounding effects of performance assessment (Xu et al., 2021)

Therefore, before creating a module capable of measuring complex psychophysiological states, a step-by-step validation of experimental paradigms should be followed (Krohn et al., 2020). This would allow for the gathering of reliable proofs of efficient physiological measures to assess live stress, VR side effects, and mental workload for work-related tasks.

3.5.2.5 SUMMARY FOR ISSUES AT DISTINGUISHING EACH SATE

This section described two main issues to measure ergonomic risks of VR: confounding effects and lack of precision when explaining which physiological responses are imputable. In-lab experimental paradigms suffer from several biases when studying VR. In summary, too often we virtually focus on one state while the other does not disappear and could explain results. The primary bias that should be considered is acknowledging that we probably miss possible alternative explanations about what is measured by only assessing one state at a time. Therefore, at least measuring possible alternative effects of VR experience is interesting. For instance, measuring cybersickness and stress or visual fatigue and mental workload, or stress and mental workload seems necessary. When looking at fundamental explanations around cybersickness, visual fatigue, and mental workload physiological response, we rely on stress-related explanations. Even if the concept of stress can apply to almost anything a human-being can encounter and needs to cope with, it seems too vague to rely on such a vast concept when assessing the psychophysiological effects of VR. Directly assessing the possible differences between cybersickness, visual fatigue, acute stress, and mental workload would better assign specific physiological variation to each state.

Distinguishing cybersickness from visual fatigue and stress and mental workload is a challenge as all those states can be characterized by similar physiological measures and seem to influence one another. Machine learning techniques are suggested to distinguish better physiological variations attributable to each state. These challenges imply that even if ergonomic risks are identified, it is still a research issue to measure them efficiently and to distinguish them.

3.6 CONCLUSIONS ABOUT ERGONOMIC RISKS OF VIRTUAL REALITY FOR LEAS

Using VR entails real ergonomic risks that cannot be avoided. Hardware providers cannot solve this in the coming years as those risks are consequent to fundamental issues. By immersing humans in VR, sensorimotor conflicts arise. They provoke cybersickness and visual fatigue. Less treated, muscle fatigue should also be considered. THE EU-OSHA already identified part of these issues (*Digitalisation and Occupational Safety and Health*, 2019). In its present form, HMDs and virtual environments to work cannot fully comply with the safety and health of LEAs workers. Even in VR, workers can be exposed to acute stress because of techno-stress (techno-complexity and techno-overload), noise, distressing materials that can lead to secondary traumatic stress, task difficulty, time pressure, and public speaking. Those stressors can negatively influence INFINITY use performances and users' well-being. Mental workload in VR seems higher than in other apparatuses. However, this does not always impact task performance negatively. Poor or inadequate interaction metaphors and interfaces could lead to mental overload and decreased task performance. Furthermore, analysts and other LEA workers could put VR aside when high time-pressure and task load require high performance if VR causes mental overload. Therefore, diagnostics of VR side effects while working is necessary to offer the best experience possible and ensure workers' safety and health.

Eye tracking, ECG, and EDA seem reliable psychophysiological sensors to measure cybersickness, visual fatigue, stress, and mental workload. A ready-for-use monitoring toolkit to measure VR side effects, acute stress, and mental overload does not exist yet. Since physiological signals can create a large amount of data and detection needs to be done with confidence, Machine Learning techniques seem necessary. Cybersickness, visual fatigue, stress, and mental overload are complex constructs. All of those states seem tangled and distinguishing each of them appears to be challenging. Bringing people into VR, e. g., to work, requires consideration of all of them to influence user well-being and performance. Measuring all those ergonomic risks should consider possible biases preventing possible overlaps between them. Cybersickness, visual fatigue, and mental overload rely on fundamental concepts very close to what can be called "stress." But this makes it hard to distinguish them.

Many challenges remain to encompass ergonomic risks when using VR to work fully. The present section aimed at cataloguing them for INFINITY partners to consider when designing the platform. This part of the report also advocates the necessity of a monitoring toolkit. But such a toolkit seems at early TRL. T2.2 of the INFINITY project will draw guidelines to consider ergonomic risks of VR at work in more detail.

3.7 OTHER IMPACTS OF USE OF IMMERSIVE ENVIRONMENT

3.7.1 MOTIVATION

Zhang (2008a), developed a theory of motivation. He listed ten principles to consider when we design technology supporting collaboration activities like in the INFINITY project. This theory is called motivational affordance and emphasizes the importance of motivation on the user's behaviour and performance (outcomes of the cognitive process).

Table 24: Design principle for achieving motivation information and communication technology (Zhang, 2008a)

Motivational Needs	Design Principles	Primary Theoretical Base
Psychological: Autonomy and the self	Principle 1. Support autonomy Principle 2. Promote creation and representation of the identity of the self	Self-determination theory (Deci & Ryan, 1985)
Cognitive: Competence and achievement	Principle 3. Design for optimal challenge Principle 4. Provide timely and positive feedback	Flow theory (Csikszentmihalyi, 1975, 1990); Goal theories (Elliot & Church, 1997)
Social, psychological: Relatedness	Principle 5. Facilitate human–human interaction Principle 6. Represent human social bond	Social interaction studies (Baumeister & Leary, 1995)
Social, psychological: Power, leadership, and 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)
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)

Principle one and two are based on the need to experience choice. The virtual environment of collaboration must leave provide autonomy to the user to manage tasks (e.g.: don't impose a time to finish a task on the informative environment/possibility to modulate avatar can support the self-definition). Principle three and four refer to the human need of competencies and achievement. The users of the communication technology and CSCW need to feel competent. They are motivated to master optimal challenges, but the complexity must be suitable to their current skills. Also, principle 4 proposes that the system provides feedback. Principles five and six are about human need to establish close emotional bonds and attachments. The system must provide interaction with others with the representation of human social bonds (audio, message, game Visio, avatar). Principles seventh and eighth are called power, leadership, and followership. They refer to the need of organisation and the conformity between the social world and the personal plan (personal and team goals, organisation, role). The system has to help the negotiation process to support the construction of a common ground and shared perception of the situation. Finally, principles nine and ten address the importance of considering the effect on the CSCW system, and a system that avoids negative affect, helping negotiation and communication can improve job satisfaction, problem solving and decision-making, and collaboration.

We can see here that motivation can impact the cognitive process and add biases or apply more complexity on the cognitive process of the LEA activities in collaboration or problem-solving. This theory helps to consider developing a virtual environment adapted to this motivation process to reduce its negative impact on the human user of the INFINITY environment.

Immersive technology can also impact extrinsic motivation to do the tasks. Still, it can also be a resource to respond to the challenges resulting from brought the LEAs activities and linked to the well-being (Hendry and Kloep, 2002, Dodge & al, 2012). On the theory of self-determination (Deci & Ryan, 2000), more often used in the field of learning, they postulate several types of motivation: intrinsic, extrinsic, and amotivation. Amotivation is the opposite of any form of motivation. Intrinsic motivation is motivation self-regulated arising from an individual's users own choice and tasks. Extrinsic motivation is motivation not directly related to the tasks, to perform for a result, to obtain something or avoid something. This theory supports the idea of a continuum of motivation, which can evolve and change from the least self-determined motivation to the most self-determined. This subsequently leads to the development of a scale of regulation of motivation, a hierarchical theory of the different levels of development, interiorization, and improvement of internal structures and representations of the individual.

As motivation can be increased, it can also be decreased because of the stress at work, the need of autonomy, human bond, and all the theories described before (Zhang, 2008a). Immersive environments can help to increase extrinsic motivation to work by the ease of data visualization or the capacity to easily improve situational awareness for example. This can increase intrinsic motivation to do the tasks and help workers, LEAs, be more involved, and support greater persistence in their activities (Pelletier, Fortier, Vallerand & Briere, 2007). Moreover, some researchers recognize a high level of immersion to have a positive impact on motivation (Richards & al, 2009 ; Dalgarno & Lee, 2010). But it is important to note that this research is performed on the learning field and not on the data analysis or work activities in general. We observe a lack of studies on this issue, not allowing us to assert that immersive technology can have a positive impact on LEAs activities.

3.7.2 AFFECT

Cognitive processes are closely related to emotions, which impact objective usability (tasks completion, time on tasks) (Mahlke, 2008). Also, involved in the objective usability for virtual environment is the flow. These two components are related, because emotions define flow, and the device can induce emotions. We will look at the relation between an immersive environment and emotions, which can impact the well-being and objective of usability (Tcha-Tokey & al, 2016).

Today's emotions are the interrelation of psychological processes, as an affective, cognitive, motivational, and physiological components (Pekrun & al, 2011). Emotions can have a positive valence or a negative valence, which means that a situation can bring enjoyment and be pleasant versus creating anxiety and/or be unpleasant (Pekrun & al, 2006). A particular form of emotion is defined as achievement emotions, directly linked to the achievements of activities, or achievements outcomes. This kind of emotion is of interest because a virtual environment bringing negative valence of achievement emotions can negatively impact the achievement of the activity, which impacts the usability of the VE. The valence of achievement emotions can be induced by the control perceived on the activities and outcomes. Feeling in control can induce positive valence, feeling out of control can induce negative valence. The interest with virtual environment can bring more feelings of control over the LEAs activities, thanks to the overview it can bring, meaning visualization and data analysis can be completed more efficiently (*previous part of deliverable 2.1 and deliverable 3.1*).

Flow is defined as a sensation felt by users when they act in total involvement (Csikszentmihalyi, 1995). Flow is also defined as a pleasant psychological state of sense of control, fun, and enjoyment. Flow can bring an increased level of usability of the VE and well-being, which can positively impact the achievement of activities (Pekrun & al, 2006). For Cheng et al. (2014), flow happens when a user interacts with the VE and perceives the whole VE to be is his/her control.

Achieving a high degree of enjoyment and flow (Tcha-toakey & al., 2017; Bowman & McMahan, 2007) depends on specific characteristics, such as: low motion frequency (0.03 Hz), active mode of interaction, visual interventions feedback and large field of view. Considering those characteristics could help to develop the INFINITY platform to creating positive emotions and flow to positively impact LEAs' work performance and well-being. We can also develop a virtual environment with a low negative impact on usability, like frustration, by taking into consideration human-VE interaction, using ergonomic criteria as suggested by Bach & Scapin (2005). They listed eight criteria to develop a VE with facilitated interaction, bringing good usability of the environment and less workload (Compatibility; Guidance; Explicit control; Significance of codes and behaviour; Workload; Adaptability; Consistency; Error management). Another study directly proposes design recommendations for VR environments (Butscher & al., 2018): (1) Support fluid workflows that allows configuring visualization; (2) Support nonlinear analysis with snapshots that allows for new analysis branches; (3) Provide sort and colorize functionalities; (4) Highlight relative differences; (5) Integrate additional non-abstract information (pictures); (6) Allow for navigating the AR space through gestures; (7) Combine navigation styles (non-egocentric or egocentric); and (8) Offer individual AR visualisation that allows reconfiguration and navigation.

While fine-grained user interactions in VR can be accomplished either via controllers or hand gestures, implications on the mental workload mainly depends on how the application utilizes the modalities. In other words, consequences on the users' mental workload can be controlled and mitigated by application design after deciding on the used modality.

Even though point-and-click interfaces using VR controllers are popular for menu navigation in VR, this is not the only option for VE interactions. VR controllers can also perform mid-air gestures and have the application to recognise those gestures by analysing either the final imaginary drawn shape or the controller's motion trajectory and the gesture's speed of execution. Similarly, combinations of hand gestures can be used to implement point-and-click interfaces that naturally arise in VR controllers' usage. For instance, this could be accomplished by having two different static gestures assigned to "pointing" and "clicking" while visualizing the 3D pointing direction in VR via 3D hand pose estimation. Essentially, this means that both point-and-click and gesture interfaces can be realized by both VR controllers and hand tracking, even though, depending on the modality, achieving a natural and intuitive feeling for the end-users may require a different design. The impact of the interaction interface on the end user's cognitive load mostly depends on the ease to learn and remember the mechanics of the interaction system. Due to the familiarity of end-users with the ubiquitous 2D mouse interface, the point-and-click interface realized by the usage of VR controllers is both easy to learn and use, imposing minimal impact on the end user's cognitive load. Provided that two easy to perform and remember "pointing" and "clicking" hand gestures can be recognized by the system, cognitive load for a point-and-click interfaces using hand tracking can also be kept to a minimum. However, point-and-click interfaces in VR are not optimal (Xiao Y., & Peng Q., 2017). Thus, on the other hand, gesture-based interfaces, realized either by VR controllers or hand tracking, require more design efforts to be effective, partially due to (at least until today) the unfamiliarity of end-users with similar interfaces and the non-existent standardization of hand gestures, unlike 2D touch gestures found in smartphones and tablets.

Fortunately, cognitive load may be minimized by past experience, essentially meaning that end-users can be more effective, efficient, and comfortable interacting with the VE after a training/learning phase. To be easy for the end-user to recall the appropriate gestures to interact with the VE, gestures need to feel natural and intuitive. However, designing a natural and intuitive gesture set is a complex task due to the multidisciplinary factors that need to be taken into consideration, except for cognitive load, e.g., ability of the recognition system to distinguish similar gestures, physical fatigue and user comfort, gesture duration, overall ease to accomplish tasks and user satisfaction levels (i.e., being fun and aesthetically pleasant) (Manresa-Yee C., 2013; Gope D. C., 2011).

3.7.3 IMPACT OF USER'S REPRESENTATION

An extensive number of studies deal with the issue how different avatar representations affect the user due to the avatar's realism, the avatar's ability to be animated in a one-to-one manner with the user, or its visible body parts. Much research focused on a series of questionnaires, both originating from the psychophysical domain developed over decades ago. Those questionnaires are based on the notions of the user's sense of presence, social presence, cognitive load, and the illusion of virtual body ownership (IVBO) (IJsselsteijn et al., 2006) in an immersive virtual environment (IVE). For an extensive review of the practices and definitions related to the aforementioned measures, the reader is referred to (Oh et al., 2018).

Presence is associated with the extent to which the users experience an IVE as belonging to the real world in which the experiment takes place, and the extent to which the users experience IVEs as places visited rather than images seen (Slater et al., 1994). The *Slater-Usoh-Steed Presence Questionnaire* was developed for measuring the user's sense of presence in an IVE. *Social Presence*'s definition is discussed in (Biocca et al., 2001), in which the *Networked Minds Measure of Social Presence Questionnaire* is presented. The authors define *social presence* as the perceived presence of another intelligent being, which can be determined by various verbal, nonverbal, visual, conscious, and subconscious signals. As already mentioned, to measure a task's cognitive load, the NASA Task Load index (Hart & Staveland, 1988) is used, using which one can make subjective workload assessments on working with various human-machine interface systems. Finally, IVBO is the illusion of owning a part of a body or an entire body other than one's own. It is used to investigate the short- and long-term impacts of embodying virtual avatars that have different qualities than a user's physical body. In this section, we provide a literature review of user representations in IVEs to the user's communication and interaction inside an IVE that utilize the aforementioned questionnaires.

Heidicker et al. (2017), develop an experiment for measuring all the aforementioned quantities, and examine three avatar categories:

- Avatar with complete body and regular predefined idle animations (*Idle*).
- Avatar with complete body and a one-to-one mapping of the user's movements to the avatar's movements (*Mapped*).
- Avatar body that consists only of a head and hands and a one-to-one mapping of the user's movements to the visible body part movements (*SocialVR*).

The participants took part in solving a collaborative task within a Unity3D VR application, using each of the avatar settings above. The order of the different avatar conditions was randomized, and all of the users completed the experiment with all of the conditions. With a view to surviving in the desert, the task the users had to solve was to sort an unordered list of survival items according to their importance. After one hour of participating, the users were asked to fill in the questionnaires. The experiment confirmed a significantly increased sense of presence in the *Mapped* setting compared to the *Idle* one, and no significant difference between the *Idle* and *SocialVR* settings. Furthermore, the sense of co-presence was increased in the *Mapped* condition, and finally, the experiment did not show any association of the task's load with a specific avatar condition.

Similarly, in (Yoon et al., 2019), the authors measured the effect of avatar appearance in AR collaborative applications regarding *social presence*. The study's independent variables were *body part visibility* and *character style* resulting in six conditions: *Realistic Whole Body* (*RWB*), *Realistic Upper Body* (*RUB), Realistic Head and Hands* (*RHH*), *Cartoon Whole Body* (*CWB*), *Cartoon Upper Body* (*CUB*), and *Cartoon Head and Hands* (*CHH*). The authors developed a simple MR remote collaboration system supporting two settings. In the first set, the users had to solve a crossword puzzle, while in the second one, the users were involved in a furniture placement task. At the end of each setting the users were asked to fill the *Networked Minds Measure of Social Presence Questionnaire.* The study suggests that the visible body parts have a considerable impact on one's sense of *social presence* by showing significant differences between avatars that contained head and hands and avatars that did not. Moreover, the study demonstrated that there is not a strong correlation between *social presence* and realistic or cartoon avatars.

An "in-the-wild" experiment is presented in (Steed et al., 2016), in which the authors develop a mobile VR application for measuring the user's sense of presence and embodiment. The experiment was set in a virtual bar, in which the user was watching a singer perform. The user was seated, facing a stage with a table in front of him/her, and another male avatar was watching the singer on the other side of the table. The experiment was parameterized with eight different conditions forming three pairs:

- Self-avatar versus no avatar (*Avatar*).
- Induction versus no induction (*Induction*).
- Singer looking at user versus not looking (*LookAt*).

Additionally, the experiment provided both male and female self-avatars. The *induction* condition involved the singer saying the words "Please tap along to the beat" immediately before the song began. The avatar then appears to tap along to the beat for about 20 sec. During the singing, a box slides off the user's table, falling on this/her knee. The questionnaires used were based on the *Slater-Usoh-Steed* and the *IVBO* questionnaires. The application was installed via a crowd-sourced approach on approximately 400 mobile devices. The experiment results indicated that the *Avatar* factor and *Induction* do impact the user's sense of presence. More specifically, the users felt that their knee was going to hurt, and they reacted when the box landed on their knee when an avatar was attached. However, while the authors expected that the *Induction* conditioned was supposed to increase the feeling of both presence and embodiment, it appeared to be counterproductive.

The realism of humanoid avatars was examined by Latoschik et al. (2017). The authors relied on the IVBO questionnaire and built a social VR application that attaches a different kind of avatars to the users. An initial study was executed between eight avatars to determine which was better suited for the main experiment. The resulting avatars were a wooden mannequin and two photogrammetry scans of real people (one for male and one for female). Two users were placed in a virtual room containing a mirror and a window, and the experiment was split in two phases, with the first one measuring the evocations of IVBO and the second one measuring the effects of seeing the other user's avatar. First, the users were asked to execute specific actions in front of the mirror. Second, the avatar of the other user appears in the window and waves at the participant, who is asked to reply and wave back. As was expected, the photogrammetry-based avatars had a significant impact on both the user's sense of presence, the acceptance of the self-avatar as the user's own body, and the acceptance of the other user as a participant in the same space. In a similar work (Lugrin et al., 2015), an experiment is performed with a humanoid-machine, an abstracted human form and realistic humans as avatars. The users were placed in a game-like environment where they were asked to find and touch targets. The study's results did not show any significant correlation between body ownership and the different kinds of avatars or task performance.

A similar study (Waltemate et al., 2018) measured the impact of the degree of personalization and individualization of users' avatars. The authors utilized three different avatars, namely a generic hand-modelled version, a generic 3D scanned version, and an individualized 3D scan, to measure how virtual body ownership, presence and emotional response are influenced depending on the specific look of the users' avatar. The experiment was split between two different virtual mirror setups. In the first one, a projection-based VR system was utilized (projecting the virtual environment on the real room in which the experiment was taking place and is generally considered less immersive). In contrast, in the second case, the user was brought into a virtual environment via an HMD. In both instances, the experiment was set with the previously mentioned types of avatars attached to the users. The experiment involved the users standing in front of a virtual mirror while being asked to perform a set of movements and instructed where to look. The users' acceptance of the avatar, and their sense of presence were generally increased for the HMD test, which means that the degree of immersion has a high impact on both factors. Finally, the study presented significantly increased body ownership and a sense of presence for the individualized scanned avatar compared to its generic counterparts.

In (Beaudoin et al., 2020), the authors analysed the impact of embodying a body of an elder human as an avatar. More specifically, they invited 52 female participants to perform a visual motor task in a virtual environment where the user was embodied with either an elderly avatar or that of a young adult. Users were initially sitting on a chair with a mirror in front of them and the other avatar (being either the elderly or the young one) sitting next to them. The task involved the users to stand up from their chair, move and sit down on another chair at some distance. The users had to say "go" when they felt ready to begin, and "stop" when they believed that they had reached the chair. The authors measured the duration between "go" and "stop" in milliseconds and the users completed the task with both the available avatars. Their experiment suggested that the more negative the belief's a participant had about the elderly, the greater the effect of the avatar had on their performance.

In (Gorisse et al., 2017) the authors conducted a series of experiments to assess the sense of presence, embodiment and the performance of users when their self-avatar is displayed in first- or third-person view. The participating users were placed in a virtual environment to perform two tasks. During the first task, the users had to deflect spherical projectiles from launchers coming from six directions, while in the second one, the users had to navigate their avatar on a platform in order to reach three terminals. The users were asked to complete all of the tasks with both viewpoint modes. The experiment's results reveal that the viewpoint mode does not have a significant impact on the users' sense of spatial presence or their ability to deflect projectiles, however the first-person viewpoint mode positively affects self-location and the body ownership factors, as well as the users' ability to navigate and perform accurate interactions within the environment.

The same authors (Gorisse et al., 2019), followed their work with a second experiment, in which they measured the impact of the avatar's visual fidelity on the user's sense of embodiment as well as their behaviour in a virtual environment. They experimented with three avatar representations, namely a robot, a suit and a doppelganger, and they invited the users to perform the following five tasks with all of the different avatar representations: **(1)** Cross a bridge; **(2)** Walk on ledges between walls whilst being careful not to fall down; **(3)** Walk slowly on a path and avoid traps that can either trigger or remove the next section of the path; **(4)** Cross an arena while dodging or blocking projectiles; **(5)** Move (or crouch) in an arena to avoid a rotating laser.

In all of the tasks, the users had to activate a virtual terminal at the task's goal. The experiment's results showed that the avatar's truthfulness plays an important role in both the user's sense of ownership and behaviour, with the doppelganger avatar positively impacting the user's embodiment and their reactions in situations which may threaten their avatar.

In another kind of work (Krekhov et al., 2019), the use of non-humanoid avatars was studied, with the authors experimenting with animal-based avatars and measuring virtual body ownership for examining the benefits and limitations of animal avatars in VR games. The experiment consisted of three avatars, a rhino, a bird, and a scorpion, each with appropriately designed actions and animations. The users were placed in an escape-room setting (different for each of the avatars) in which they had to use each of the avatars features to escape from the room. The IVBO questionnaire was given to each user after each trial. The study presented a strong correlation between game enjoyment and body ownership. The additional body parts or a non-human body shape do not inhibit an avatar's potential to induce IVBO.

Finally, by considering the research results discussed in this section, we can make the following conclusions. Firstly, the appearance of an avatar in terms of realism does not seem to greatly impact its acceptance by the user, i.e., the users' sense of body ownership is relatively equal for both cartoon and realistic avatars. However, the same cannot be said for the case of non-humanoid avatars, as the study of (Krekhov et al., 2019) could disentangle game enjoyment from body ownership. Additionally, the realism of the avatar does not seem to affect the cognitive load of a given task. On the other hand, the visible parts of the avatar play a significant role in the users' sense of *presence*, *social presence,* and the *illusion of body ownership*.

4 CONCLUSION AND PERSPECTIVES

1. Immersive technologies have positive and negative impacts on the users

We have introduced the main components to be considered while designing immersive environments and how they can impact on the user. These are active research fields, and although some answers are already available, many questions and issues are still open. Although benefits and positive outcomes are expected from the use of immersive technologies, such as VR and AR, it is essential to note that negative impacts also exist. This is relevant for the cognitive aspect: the project's ambition is to allow users to interact with the data in a new way, to be immersed into the data instead of just interacting with 2D representations of the data. Such new representation may be interesting to facilitate the understanding of complex data, but we have also identified that such a new interface may, by itself, bring complexity and disturb the cognitive process**. All of these should be carefully balanced in the INFINITY project to allow users to take advantage of the benefits while limiting the negative impact.**

2. Several tools and parameters can be measured to monitor the user experience

An important aspect that has also been addressed in this document is evaluating such positive and negative impacts. Different parameters have been identified. However, processes and mechanisms that are considered and the users' states (physical and mental) that are monitored are not always easy to distinguish. Furthermore, many interactions and co-variances occur. Two main approaches exist: objective and subjective evaluations. Objective evaluation currently requires the use of several external devices to measure physiological parameters. Such objective measures can be combined with questionnaires to collect subjective user feedback. Subjective evaluations have been described and several questionnaires presented that can be used in the project. Evaluation of impact is also an active research field that will be facilitated by the development of devices and the possibility of sensors embedded into the HMD, as is also the case for eye tracking. However, this will raise the issue of personal data collection and management (Cavedoni et al., 2020; Kröger et al., 2020; Liebling & Preibusch, 2014; M. R. Miller et al., 2020). The question of the user impact is essential, as the evolution of technologies may also increase the potential impact on the users, for instance, with the development of 5G networks and the potential impact of electromagnetic radiation. **This is part of the project's ambition to develop and test tools to collect user data and monitor the user experience.**

3. Perspective

Based on these preliminary findings, INFINITY partners will draft recommendations for the design of the immersive environment (D2.2) and the monitoring of the impact on the user (D7.6):

- Identify which kind of tasks VR / AR / MR is most relevant, to optimise positive effects / limit side effects
- Provide a framework for guidelines and impact evaluation during piloting
- Minimum technical requirements for mitigating negative impacts
- Checklists for supervisors to monitor the impacts and to decide on necessary breaks or the improvement/modification of the equipment
- Training for LEA's on the proper and least stressful use of AR/VR headsets

This document relates to the user impact only, and other kinds of impacts have not been considered, such as the ecological impact of XR and the life cycle of XR headsets. This may also be relevant but should be conducted later on as the system's architecture, which is not yet defined, may have a significant impact upon these questions.

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