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ORIGINAL ARTICLE

A narrative review of immersive virtual reality's ergonomics and risks at the workplace: cybersickness, visual fatigue, muscular fatigue, acute stress, and mental overload

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Abstract
This narrative review synthesizes and introduces 386 previous works about virtual reality-induced symptoms and effects by focusing on cybersickness, visual fatigue, muscle fatigue, acute stress, and mental overload. Usually, these VRISE are treated independently in the literature, although virtual reality is increasingly considered an option to replace PCs at the workplace, which encourages us to consider them all at once. We emphasize the context of office-like tasks in VR, gathering 57 articles meeting our inclusion/exclusion criteria. Cybersickness symptoms, influenced by fifty factors, could prevent workers from using VR. It is studied but requires more research to reach a theoretical consensus. VR can lead to more visual fatigue than other screen uses, influenced by fifteen factors, mainly due to vergence-accommodation conflicts. This side effect requires more testing and clarification on how it differs from cybersickness. VR can provoke muscle fatigue and musculoskeletal discomfort, influenced by fifteen factors, depending on tasks and interactions. VR could lead to acute stress due to technostress, task difficulty, time pressure, and public speaking. VR also potentially leads to mental overload, mainly due to task load, time pressure, and intrinsically due interaction and interface of the virtual environment. We propose a research agenda to tackle VR ergonomics and risks issues at the workplace.

Keywords Virtual reality · Ergonomics · Cybersickness · Visual fatigue · Muscle fatigue · Stress · Mental overload · Work

1 Introduction

There is increasing consideration of replacing parts of current work involving a PC (using mouse and keyboard) with immersive virtual reality (VR) by both industry and scientists (Filho et al. 2018, 2019, 2020; Guo et al. 2019a). Democratization of nomad and remote work is a common argument for office-like experiences in VR (Grubert et al. 2018; Ofek et al. 2020). Literature contributions started to analyze the transposition to VR from a PC for various tasks. This includes spreadsheets (Gesslein et al. 2020), text entry (Knierim et al. 2018; Speicher et al. 2018a), editing and proofreading (Kim and Shin 2018; Li et al. 2021), reading (Baceviciute et al. 2021; Rzayev et al. 2021), coding (Castelo-Branco et al. 2021), and information retrieval (Schleußinger 2021). A growing number of contributions present VR with possible benefits in various fields. However, many scientific challenges remain for VR daily adoption in office-like tasks. One of them is health and safety implications (LaViola et al. 2017; Fuchs 2018; Khakurel et al. 2018; Çöltekin et al. 2020; Olson et al. 2020; Anses 2021; Ens et al. 2021). Virtual environment creators and head-mounted display (HMD) manufacturers do not seem to consider human factors/ergonomics enough in their design processes (Dehghani et al. 2021; Saghafian et al. 2021; Szopa and Soares 2021). However, virtual reality-induced symptoms and effects (VRISE) have been documented for more than thirty years (Kennedy et al. 1993; Keller and Colucci 1998; Cobb et al. 1999; Nichols 1999; Nichols and Patel 2002; Sharples et al. 2008; Melzer et al. 2009; Fuchs 2017, 2018; Souchet 2020; Grassini and Laumann 2021).

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Contributions about VR use for office-like tasks rarely mention or assess possible VRISE risks.

The EU-OSHA has already identified VRISE risks in a brochure on digitalization (EU-OSHA 2019). VRISE are real problems that elicit a negative user experience (Somrak et al. 2019; Lavoie et al. 2020). Concretely, workers might become sick or suffer from side effects, possibly reducing their task performance (Mittelstaedt et al. 2019; Mittelstaedt 2020; Park et al. 2021). Although the contradicting results show no significant correlation between cognitive performance and VRISE, such as cybersickness (Varmaghani et al. 2021), there is a definite need to consider possible VR side effects in everyday work to anticipate normalization or future regulation guidelines. Above all, designers and employers should safeguard workers' health and safety if they use VR. This can only be achieved if all stakeholders know VR benefits and risks.

We concentrate on typical office-like tasks workers mainly fulfill with a PC. Usually, previous works would concentrate on one possible VRISE at a time. However, possible confusions are maintained between cybersickness (visually induced motion sickness) and visual fatigue. Moreover, other possible issues such as muscle fatigue, acute stress, and mental overload are rarely considered when measuring VRISE. Chen et al. (2021) gather several ergonomic risks of HMDs, but they do not comprehensively propose a general approach and an exhaustive list of influencing factors. Stanney et al. (2020b) focused on cybersickness and did not separate it from other VRISE.

This article considers five specific risks: cybersickness, visual fatigue, muscular fatigue, acute stress, and mental overload. It is worth noting that we mainly concentrate on acute symptoms, not chronic ones, based on repeated VR use since very few studies directly address medium- to long-term side effects. Yet, Howarth and Hodder (2008) found that 50% of users no longer had any symptoms after ten sessions every two to seven days. Our purposes are to.

- catalog the main VR ergonomic risks at work by referring to recent publications with new HMD generation
- point the distinction between cybersickness and visual fatigue
- consider other risks than cybersickness
- better inform VR users and designers about the risks inherent in this technology if they want to introduce it at the workplace

The article is structured as follows. First, we describe the method to search previous works. Second, we present the results from this search on cybersickness, visual fatigue, muscle fatigue, acute stress, and mental overload. For each VRISE, we draw an overview and occurrence description based on previous meta-analyses, systematic reviews, or overviews when available. For each VRISE, we propose a synthesis of possible factors evoked in the literature as inducing symptoms. The review encouraged us to add a disambiguation section in virtual reality relating to cybersickness. Then, we introduce works assessing office-like tasks in VR about each VRISE that can help better gauge risks. Third, we discuss the results about each VRISE, the limitations of our review, and provide a research agenda for theoretical and experimental works that better define, quantify, and distinguish each ergonomic risk.

2 Method

2.1 Keywords and database

Initial papers' selection was made in August 2021 based on the following keywords for each VRISE: "cybersickness" OR "visually induced motion sickness," "visual fatigue" OR "eyestrain," "muscle fatigue" OR "musculoskeletal discomfort," "stress" OR "acute stress," "mental workload" OR "cognitive load, AND "Virtual reality" AND "work" AND "meta-analysis" OR "Systematic review" OR "Review" in Google Scholar. We used the same keywords listed above to document VRISE at work without adding meta-analysis, systematic review, or review.

2.2 Inclusion and exclusion criteria

Papers were included if.

- Published between 2016 and 2021
- Language used was English and French
- Peer-reviewed or grey literature written by scientists
- Mentioning one searched keyword at least in whether the title, abstract or list of keywords
- Using HMDs available for the general public

Papers were excluded if.

- Using other languages than English or French
- Not mentioning keywords, at least in whether the title, abstract, or list of keywords
- Not using off-the-shelf HMDs
- Subjects in experiments were children
- Stimuli are video games that require interactions or stimuli too far from office-like tasks in VR

2.3 Search strategy

We concentrated on articles published between 2016 and 2021. 2016 has been selected as the starting date of literature research because it corresponds to Oculus CV1's commercial release, making the HMD widely accessible for labs and allowing overview contributions to incorporate new generation HMDs. If the latest review, systematic review, or meta-analysis was published before 2016, we augmented the range to years before 2016 until finding a result. When the latest meta-analysis, systematic review, or review paper was found, we extracted information to write our overview of VRISE and its occurrence. If no meta-analysis, systematic review, or review existed, we draw factors from individual papers proposing them. The procedure described here, including the criteria, mostly refers to the description of VR in the work environment. The general presentation of VRISE mostly mixes latest review papers and older contributions.

3 Results

3.1 Cybersickness

3.1.1 Cybersickness overview

The following symptoms characterize cybersickness: visual fatigue, headache, pallor, sweating, dry mouth, full stomach, disorientation, dizziness, ataxia (movements coordination), nausea, and tiredness (Lawson 2014; Davis et al. 2014; Rebenitsch and Owen 2016; Bockelman and Lingum 2017; Nesbitt and Nalivaiko 2018; Descheneaux et al. 2020; Chang et al. 2020). During the first popularization phase of HMDs in the 90 s, there was optimism about the ability to “cure” cybersickness (Biocca 1992). However, thirty years later, the issue still exists, as documented by the latest overviews (Stanney et al. 2020b). Cybersickness arises no matter the HMD (Yildirim 2020). Therefore, despite HMD technical improvements, cybersickness is not likely to disappear anytime soon (Gallagher and Ferrè 2018). However, the current HMD generation seems to cause fewer risks than previous generations (Caserman et al. 2021).

Several competing theories exist to explain and predict the cybersickness phenomenon: sensory conflict, evolutionary, ecological (postural instability), and multisensory reweighting (Palmisano et al. 2020a; Stanney et al. 2020b). The sensory conflict theory of motion sickness (or sensory cues conflict) is the most widely accepted (Lackner 2014; Stanney et al. 2020b). According to this theory, passive movement creates a mismatch between information relating to orientation and movement, provided by the visual and the vestibular systems (Colman 2009).

As Watt (1983) recalls, Reason (1978) explains that motion sickness results from a mismatch between predicted and actual sensory inputs in his theory description. Constancy is disturbed within the virtual environment due to sensorimotor conflicts (Patterson et al. 2006; Patterson 2009). “Sensorimotor” represents sensory and motor elements necessary for an individual to interact with their environment (Ehrenbrusthoff et al. 2018). Most conflicts in virtual environments are visually induced (Rebenitsch and Owen 2016). Our “probabilistic brain” (Pouget et al. 2013), which seems to rely on predictive computation to perceive, process, and interact with the natural environment (Diaz et al. 2013; Van den Berg et al. 2015; Mahani et al. 2017; Alais and Burr 2019; Walsh et al. 2020), faces inconsistent and unreliable cues from virtual environments. An alternative explanation is that our brain, via error minimization, could also reweigh each sensory signal (Gallagher and Ferrè 2018) to reduce unpredictability. The main criticism of sensory cue conflict is that the theory is not falsifiable (Stanney et al. 2020b).

The evolutionary theory states that the resulting illness is derived from prior evolutionary adaptation to the effects of poison (Treisman 1977; Stanney et al. 2020b). The body essentially misinterprets the symptoms caused by inconsistent cues as poison.

The ecological theory states that cybersickness is due to the body's inability to compensate for its posture given the external stimuli properly. An increase in deviation from ideal posture is thought to indicate more significant illness. The primary criticism of the ecological theory is that the severity and type of postural instability vary across VR environments (Munafo al. 2017), and illness may occur with no instability (Dennison and D’Zmura 2017).

However, the exact psycho-physiological causes and the most parsimonious theories are not sufficient to explain cybersickness (Davis et al. 2014; Nesbitt and Nalivaiko 2018; Weech et al. 2018; Descheneaux et al. 2020; Stanney et al. 2020b; Howard and Van Zandt 2021). Therefore, the actual models describing and explaining cybersickness remain under debate.

Two aspects of cybersickness research continue to cause controversy:

1) A unifying theory is still missing. Hence, more contributions under each competing prediction are needed.
2) Various strategies exist to tackle cybersickness’s prediction. To deploy and assess each strategy, objective and subjective measurements are necessary.

Cybersickness is one concern for workers using VR. Hereafter, we describe cybersickness occurrence based on the current state of the art.

3.1.2 Cybersickness occurrence

According to Stanney et al. (2020b), at least one-third of users will experience discomfort during VR usage, and 5% will present severe symptoms with the current HMD generation. Although, in some contexts, it can be up to 80% (Kim

Table 1 Possible factors inducing cybersickness according to Rebenitsch and Owen (2021)

Individual	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	

et al. 2005). Rebenitsch and Owen (2021), following Laviola (2000) and Davis et al. (2014), list three types of factors affecting VR experience and cybersickness. See Table 1 for an organized list of the factors.

We rearranged Rebenitsch and Owen's (2021) factors into individual (demographics in their contribution), hardware (former device factor), and software categories (former task factor) compared to Davis et al. (2014) in Table 1. According to Rebenitsch and Owen (2021), at least fifty factors could influence cybersickness. It should be noted that perceptual style, which is listed under mental attributes in individual factors (see Table 1), is linked to learning style and is criticized as a neuromyth (Willingham et al. 2015; Kirschner 2017). The documented higher risks of symptoms in women, which is the Gender factor listed in Individual factors (see Table 1), in past works could be due to the general ergonomics of current HMDs and higher average motion sickness susceptibility (Stanney et al. 2020a). However, there is no consensus about gender differences as data acquired by previous works are questionable (Grassini and Laumann 2020; MacArthur et al. 2021).

Latency or lag, listed under Screen in Hardware factors (see Table 1), can impact cybersickness. However, to date, the magnitude is still unclear as experiments are drastically varying (latency measures, paradigms, etc.) (Stauffert et al. 2020). Rebenitsch and Owen (2021) also point out that the initial lag factor had been determined with old apparatuses and argue that it is less likely to occur with new HMDs due to better performances.

Cybersickness increases with exposure time (Dennison et al. 2016). The duration factor, listed under experience in individual factors (see Table 1), is widely pointed out as one of the main contributors to cybersickness in appearance and magnitude (Dużmańska et al. 2018).

Standing rather than sitting increases the chances of provoking cybersickness (Merhi et al. 2007), as Rebenitsch and Owen (2021) mentioned. Therefore, defining whether users should use VR applications while sitting is necessary for work purposes.

Other factors than the list by Rebenitsch and Owen (2021), mainly individual, might influence cybersickness (Howard and Van Zandt 2021). Here is a list pointing at individual factors that could also influence cybersickness (pathologies, neurodiversity):

- Emotional personalities reported the highest oculomotor, disorientation, and VR sickness scores (Widyanti and Hafizhah 2021)

- Smoking seems to be a predictor of cybersickness in highly stressed people (Kim et al. 2021)
- Insomnia seems to impact vestibular, oculomotor, and interoceptive functions, leading to more visually induced motion sickness (Altena et al. 2019).
- Autism spectrum disorders might cause users to suffer from higher adverse symptoms (Schmidt et al. 2021).
- Multiple sclerosis could affect people differently from the general population as these users have balance impairments (Ferdous et al. 2018), less alertness, more stress, and possibly lower attention (Arafat et al. 2018).
- Age-related macular degeneration (arising starting at 50) seems to result in an increased rate of less perceived vection strength, and those with early manifest glaucoma reported lower perceived vection strength but also lower cybersickness than the "normal" population (Luu et al. 2021a).
- Alcohol (intoxication at a blood alcohol level of approximately 0.07%) seems to alleviate cybersickness (Iskenderova et al. 2017).
- Prior information or a questionnaire about cybersickness can provoke priming or anchoring effects (Furnham and Boo 2011; Weingarten et al. 2016; Doherty and Doherty 2018). Users report more side effects when expecting them (Almeida et al. 2018).

Even though short-term side effects of VR are well known, impacts on cognition and long-term effects are yet to be documented. However, based on questionnaires like the simulator sickness questionnaire (Sevinc and Berkman 2020; Hirzle et al. 2021), physiological changes that correlate to subjective reports have been documented by Gallagher and Ferrè (2018). According to Gallagher and Ferrè, cybersickness influences psycho-physiological variables that can be measured with ECG (Electrocardiography, heart), EDA (Electrodermal activity, skin), or EEG (Electroencephalography, brain). Blink rate increase with exposure time and cybersickness (Lopes et al. 2020). Therefore, we can also add to Gallagher and Ferrè's (2018) list the incidences on the visual system.

During and after VR exposure, users report symptoms correlated with psycho-physiological changes. Rebenitsch and Owen's (2021) list of factors influencing cybersickness to go beyond classic motion sickness symptoms and vection issues (visually mediated subjective experience of self-motion). However, cybersickness is mainly explained by visually induced motion. Therefore, it is necessary to understand if cybersickness could arise with office-like tasks.

3.1.3 Cybersickness and working in VR

Most experimental contributions on cybersickness use video games (rollercoasters), driving tasks, or dedicated "walking-around" tasks. Those paradigms induce cybersickness symptoms with some confidence to measure psycho-physiological variations attributable to it. However, even if those previous works provide useful information, we narrowed down the literature presented to work-related tasks to match office-like tasks. Ten articles met inclusion/exclusion criteria.

In a collaborative car design environment, Coburn et al. (2020) experimented with four moving methods: teleport, fade, fly, and manual. (Translation and rotation automatically place users in a predetermined location.) After moving, participants located a particular part of the car. Flying proved to be the best solution for spatial location. But it implied a potentially higher discomfort (cybersickness). In their experiment, teleporting was the worst mode because of disorientation. Coburn et al. (2020) advocate multiple transition styles (locomotion) for users. We can hypothesize that users in a VR application for office-like tasks will be sitting (Zielasko et al. 2017; Zielasko and Riecke 2021). Zielasko et al. (2019) had participants move by leaning (forward and backward). Participants found the shortest path between a pair of red vertices hidden in a node-link visualization. Since participants were sitting in front of a desk, Zielasko et al. (2019) tested two conditions: a stable virtual desk visually represented in VR and without a virtual desk. The author did not find differences in cybersickness (and task performance) when employing a keyboard and other interfaces instead of a virtual desk.

When analyzing data, the type of locomotion also seems to be impacted by the user's expertise in data analysis, video games, and spatial orientation ability (Lages and Bowman 2018). Some works show no difference in cybersickness symptoms when comparing real desk tasks to a virtual reality desk (Guo et al. 2019a). Boges et al. (2020) work (editing and exploring medial axis representations of nanometric scale neural structures) shows that users must take several breaks because of cybersickness after being immersed for fifteen minutes. However, side effects in experimental contributions are not always assessed, such as in works about data visualization in VR, e.g. (Andersen et al. 2019). In office-like work in VR, visually induced motion sickness could be less of a problem since fewer tasks or stimuli require 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 have shown that cybersickness needs further investigation and acknowledged as a risk of side effects even in this configuration. Locomotion and visual feedback of this locomotion are two crucial factors leading to cybersickness (Caserman et al. 2021).

Based on the latest reviews and systematic reviews (Koohestani et al. 2019; Descheneaux et al. 2020; Kemeny et al. 2020; Saredakis et al. 2020; Stanney et al. 2020b), we can infer that contributions regarding cybersickness concentrate on the visual-vestibular-proprioceptive conflicts (like motion sickness) issue. Contributions rarely focus on visual fatigue, i.e., vergence-accommodation conflict (Fuchs 2017; Souchet 2020; Chang et al. 2020; Souchet et al. 2021a). But Rebenitsch and Owen (2017) reported no effect of vergence-accommodation conflict on cybersickness.

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 (Chang et al. 2020). Nausea may only result in 30% of the instances after withdrawing from VR use (Rebenitsch and Owen 2017). Our current focus choice aligns with the agenda of Stanney et al. (2020b) as we contribute to the evaluation and applications research to tackle cybersickness issues. This section shows that oculomotor symptoms are mainly induced by visual motion in VR. But visual fatigue should be considered not only as a symptom related to cybersickness but as a side effect of its own. Therefore, the following section addresses visual fatigue, as cybersickness seems heavily dependent on locomotion, less of a determinant feature in office-like VR applications.

3.2 Visual fatigue

3.2.1 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 (Lambooij et al. 2007, 2009). 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 and IJsselsteijn (2009) define visual fatigue as a "*physiological strain or stress resulting from excessive exertion of the visual system.*" Various screen usages induce 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 HMDs or other devices displaying stereoscopy.

HMDs are absent of most visual fatigue reviews, such as in Coles-Brennan et al. (2019) for standard displays. One of the main issues regarding visual fatigue is that HMDs are displaying stereoscopic images: depth cues from the environment inferred from the distance between our two eyes (interpupillary-distance) fused by our brain (Parker 1983, 2016; Hodges and Davis 1993; Best 1996; Reichelt et al. 2010; Holliman et al. 2011; Urey et al. 2011; Rößing 2016).

Terzić and Hansard (2017) reviewed the causes of visual discomfort, pointing to future problems with HMDs since the apparatuses display stereoscopy. Displaying stereoscopy is known to induce visual strain in general (Lambooij et al. 2007, 2009; Kuze and Ukai 2008; Fortuin et al. 2010; Kim et al. 2011; Karajeh et al. 2014; Sugita et al. 2014; Sasaki et al. 2015). However, the scientific literature is unclear on the mechanisms and predictions distinguishing visual fatigue from cybersickness.

3.2.2 Visual fatigue occurrence

Despite all the excessive exertions on the visual system when using HMDs, they do not seem to induce myopia after 40 min of exposure (Turnbull and Phillips 2017). However, HMD use can contribute to near-work factors that induce myopia, and the impact on accommodation and vergence functions also could be a long-time concern (Németh et al. 2021). Therefore, we concentrate on visual fatigue rather than other issues that could arise with users' eyes since we are concerned with what happens while VR is used.

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 that the effect can only be seen with two eyes (Blake and Wilson 2011). The horizontal distance between the eyes (inter-pupillary distance) is on average 65 mm (Anses 2014), ranging from about 50 to 77 mm for the general population (Lambooij et al. 2009; Stanney et al. 2020b). However, this range may vary depending on the country and gender and be wider if children are included (Dodgson 2004; Stanney et al. 2020a). Misadjustments of HMD lenses, in the form of binocular stimuli related to IPD, can provoke visual fatigue (Hibbard et al. 2020).

Disparity and blur drive the vergence and accommodation mechanisms (Sweeney et al. 2014). According to Schor and his colleagues' model (Schor and Kotulak 1986; Schor and Tsuetaki 1987; Schor 1992), vergence and accommodation are two dual parallel feedback control systems that interact via cross-links. Lambooij et al. (2009) summarized that 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°. Fusion without diplopia

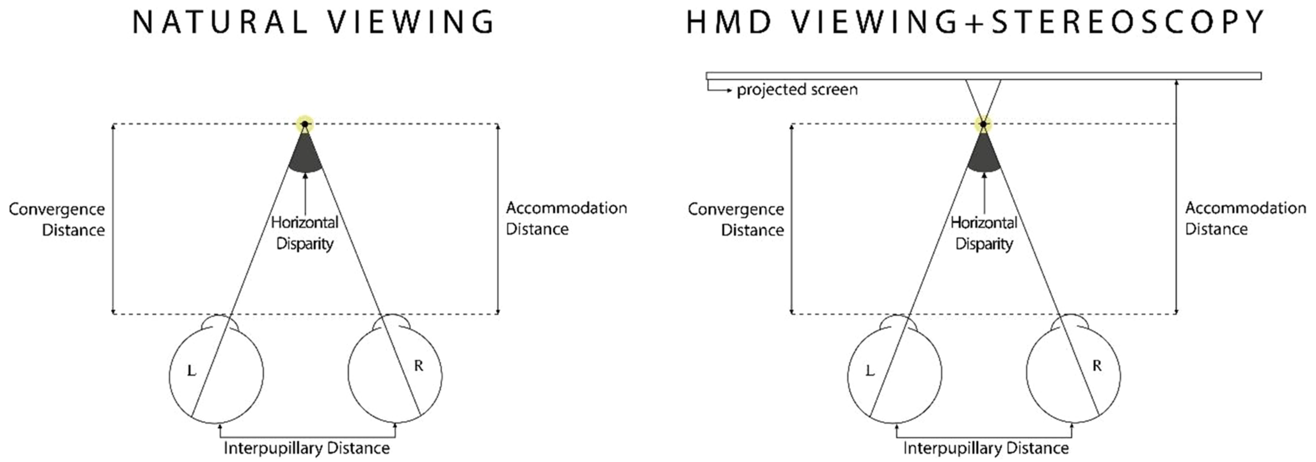

Fig. 1 Comparison of natural binocular viewing and HMD viewing with stereoscopy (near object, negative parallaxes in this example): accommodation and convergence occur on the same plane in natural viewing but in HMD viewing with stereoscopy, there is a mismatch between accommodation and vergence that are crosslinked mechanisms

Table 2 Possible factors inducing visual fatigue in VR based on a synthesis of previous works update of Bando et al. (2012)

Individual	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
	HMD resolution	Blur
		Colors

(double vision) is possible (Patterson 2015). Retinal disparity on the horopter is about 0°. Shibata et al. (2011) assume that the maximum and minimum relative distance of the comfort zone is between 0.8 diopters and 0.3 diopters. Stereoscopy sometimes requires fusion outside of the comfort zone (Lambooij et al. 2009; Fortuin et al. 2010). When this occurs, the habitual crosslink between accommodation and vergence is mismatched because accommodation applies to the screen's plane while convergence applies to objects of interest (Emoto et al. 2005; Banks et al. 2013; Kim et al. 2014; Leroy 2016; Fuchs 2017) (see Fig. 1). Several scientific works treat accommodation and vergence mechanisms and conflicts due to stereoscopy in detail (Schor 1992; Jiang et al. 2002; Hoffman et al. 2008; Lambooij et al. 2009; Mays 2009; Banks et al. 2012, 2013; Kim et al. 2014; Leroy 2016; Neveu et al. 2016; Rößing 2016; Fuchs 2017).

Stereoscopy induces the vergence-accommodation conflict (Ukai and Howarth 2008; Bando et al. 2012). This conflict also arises with HMDs (Yuan et al. 2018; Matsuura 2019). There is no theoretical consensus on which to rely, but this conflict concerns everyday VR uses (Biggs et al. 2018). This sensorimotor conflict mainly explains visual fatigue with HMDs (Fuchs 2017). A new generation of HMDs still causes visual fatigue (Souchet et al. 2018, 2019, 2021a; Hirota et al. 2019; Wang et al. 2019; Yoon et al. 2020) and visual discomfort (Cho et al. 2017; Guo et al. 2017, 2019b; Souchet et al. 2018; Bracq et al. 2019). A lack of contributions to document that effect (beyond merely knowing that it still exists for HMDs) has been pointed out (Szpak et al. 2019). Table 2 updates the list of factors proposed by Bando et al. (2012).

Visual fatigue appears to be time-related: the more prolonged the VR exposure, the higher the visual fatigue. Guo et al. (2019b) find that symptoms are increasingly severe and that the severity increases faster during the first 20 min. Guo et al. (2020) tested exposures of almost eight hours to VR and reported increasingly impacted accommodative response and pupil size. However, the impact is comparable with VR and 2D screen working tasks (text error corrections) for pupil size. Specific cumulative effect of immersion on eye movement (extraocular muscle excitation) has been observed while calculating a visual fatigue index through ocular biomechanics by Iskander and Hossny (2021)

Apart from the population that is "stereo-blind," have missing or have non-measurable binocular depth perception, the proportion of concerned individuals varies according to the tested populations and measurement conditions from 2.2% to 32% (Lambooij et al. 2009; Bosten et al. 2015; Hess et al. 2015). Moreover, although not necessarily impacting the discriminating abilities to determine an object's depth, the precision abilities of stereopsis diminish with age (Schubert et al. 2016). It also seems that poor stereo acuity drives higher visual fatigue (Ramadan and 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 significant this factor is since little research has been conducted, especially with HMDs (Heo et al. 2017; Lawrenson et al. 2017; Priya and Subramaniyam 2020; Tu et al. 2021). Continuous (chronic) exposure to blue light might damage the retina (Ahmed et al. 2018). Since HMDs use OLED and LCD technologies, this suggests that blue light could be a factor of visual fatigue when using VR. Previous stereoscopy and near-work contributions indicate that blue light implies less accommodation (Panke et al. 2019).

Several more display features are associated with visual fatigue. The lighter the displayed stimuli, the higher the visual fatigue (Wang et al. 2010; Erickson et al. 2020). The more frequent the color changes, the higher the visual fatigue (Kim et al. 2016). The more dynamism in videos, the more visual fatigue (Kweon et al. 2018). An Anses[1] report about light effects on health includes blue lights (range from 400 to 490 nm). It 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.

Blue light seems to facilitate visual discomfort in general (not restricted to screen use). However, according to the report, proof of effects on humans is limited. Long-term issues include (Anses 2019) 1) disturbance of circadian rhythms in the form of disturbance of sleep if exposed to blue lights 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 (Niwano et al. 2019; Mehra and Galor 2020). However, it is not clear how much blue lights emitted by HMDs influence visual fatigue.

Other possible factors that might influence visual fatigue but that has yet to be further tested in the VR context (therefore, we did not list them in Table 2), including the following:

- Passive smoking and e-cigarettes have similar negative impacts on tear films, and smoking regular cigarettes is detrimental to the tear film (Miglio et al. 2021). This implies that dry eye syndromes would be more likely to arise in those situations, possibly hastening the development of visual fatigue when using VR.
- Vergence and accommodation insufficiency is associated with less task engagement and higher cognitive fatigue during complex tasks (Bernhardt and Poltavski 2021). Visual fatigue can also negatively impact attention (Yue et al. 2020). Therefore, mental workload might influence visual fatigue (Daniel and Kapoula 2019; Bernhardt and Poltavski 2021).

Usually, visual fatigue is measured before and after HMD use. But, HMDs increasingly implement eye trackers, allowing measurements during immersion (Souchet et al. 2021b). But, no measurement method for visual fatigue caused by HMDs has reached a consensus. Factors inducing visual fatigue and cybersickness are sometimes similar (see Tables 1 and 2). This similarity does not help to clarify the domain of visual fatigue and the domain of cybersickness. In both cases, oculomotor performance seems to be negatively impacted in VR (Valori et al. 2020). In the next section, we try to disambiguate cybersickness from visual fatigue.

3.2.3 Disambiguation of cybersickness and visual fatigue

Vi sual fatigue is listed as one of cybersickness's symptoms (Lawson 2014; Davis et al. 2014; Rebenitsch and Owen 2016; Bockelman and Lingum 2017; Nesbitt and Nalivaiko 2018; Descheneaux et al. 2020; Chang et al. 2020). However, visual fatigue and visually induced motion sickness seem different but with a small relation (Bando et al. 2012; Yuan et al. 2018; Wang et al. 2019). Hereafter, we develop each argument advocating for two different VRISE measurements.

3.2.3.1 Visual fatigue and cybersickness intersect theoretically but do not rely on the same theories Visual fatigue predictions in VR mostly reuse knowledge drawn from stereoscopic images and their perception without discomfort (Lambooij et al. 2009; Terzic and Hansard 2017). Most contributions point to vergence-accommodation conflict as the main factor explaining visual fatigue with HMDs (see Sect. 3.2.2). Patterson proposes the "Dual-process theory" to predict visual fatigue occurrence with stereoscopic images (Patterson 2009; Patterson and Silzars 2009; Evans and Stanovich 2013). However, when describing the vergence-accommodation conflict

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[1] French Agency for Food, Environmental and Occupational Health & Safety.

occurring with HMDs – or only stereoscopy – most peers point to “sensorimotor conflicts” during visual perception (Bando et al. 2012; Fuchs 2017). They do not rely on Patterson’s proposal or other transparent theoretical backgrounds. This view relies on the sensorimotor approach and sensorimotor contingencies theory, indicating that perception (especially sight) is intimately linked to motor actions (O’Regan and Noë 2001; Buhrmann et al. 2013; Dell’Anna and Paternoster 2013; Bishop and Martin 2014).

From the perspective of sensorimotor contingencies, accommodation-vergence conflict is failing our brain’s probabilities. Thus, the accommodation-vergence mismatch can be considered a sensorimotor conflict. The mismatch impacts the crosslink between the accommodation-vergence components resulting in a sensory conflict during depth perception and drives to excessive oculomotor movements.

It should be noted that the concepts of predictive coding and sensorimotor contingencies theory are in debate in the cognition field and are not reaching a consensus (Flament-Fultot 2016; Vernazzani 2019; Williams 2020; Marvan and Havlík 2021). Ukai and Howarth (2008) conclude their review by stating that the theory applying to visual fatigue provoked by vergence-accommodation conflict remains unclear. Therefore, our description of sensorimotor contingencies theory as a possible candidate should be taken with caution because 1) it drifts from the current views in cognition that humans have an internal representation of the outside world in line with current developments of controversial “embodied cognition” (Adams 2010; Goldinger et al. 2016), and 2) it is not directly used by previous works to explain the accommodation-vergence conflict in VR. However, peers refer to sensorimotor conflicts to explain accommodation-vergence conflicts with HMDs.

In parallel, cybersickness's “evolutionary theory” provides predictions about vergence-accommodation conflict (Stanney et al. 2020b). However, as introduced in Sect. 3.1.1, the theory most widely employed is the sensory conflict theory of motion sickness. Vergence-accommodation conflict is usually listed in cybersickness descriptions (Nesbitt and Nalivaiko 2018; Descheneaux et al. 2020; Chang et al. 2020; Stanney et al. 2020b; Rebenitsch and Owen 2021) but without clearly demonstrating if it is predicted by the sensory conflict theory of motion sickness. Like visual fatigue in VR, cybersickness relies on the concept of conflicts between “sensorimotor” systems (Weech et al. 2018; Stanney et al. 2020b).

In summary, it appears that visual fatigue in HMDs could rely on sensorimotor contingencies theory which mainly applies for predicting visual fatigue due to vergence-accommodation conflict: visual-proprioceptive (oculomotor) conflicts. In contrast, cybersickness relies on the sensory conflict theory of motion sickness, mainly predicting visual-vestibular conflicts. However, both theories are debated, and no clear consensus advocates that those theories apply.

3.2.3.2 Visual fatigue and cybersickness intersect in symptomology

Cybersickness and visual fatigue overlap as lists of symptoms for the first include the second. Cybersickness describes several oculomotor symptoms. Questionnaires, like the virtual reality sickness questionnaire (VRSQ) designed for cybersickness (Kim et al. 2018; Sevinc and Berkman 2020; Cid et al. 2021), or the simulator sickness questionnaire (SSQ) by Kennedy et al. (1993), list similar symptoms to those for visual fatigue like the computer vision syndrome questionnaire (CVS-Q) (Seguí et al. 2015; Sheppard and Wolffsohn 2018) or questionnaires developed for discomfort during stereoscopic viewing (Lambooij et al. 2007, 2009; Zeri and Livi 2015). Namely, “headache” and “blurred vision” are common symptoms reported for both states. Questionnaires about visual fatigue in VR usually have not been designed to assess HMD-viewing context directly. In summary, we can see that cybersickness and visual fatigue intersect on at least two symptoms.

3.2.3.3 Visual fatigue and cybersickness influencing factors intersect

Common possible factors can influence both cybersickness and visual fatigue (see Tables 1 and 2): age, stereoscopic visual ability, optical misalignment (inter-pupillary distance in Table 1), global visual flow (motion parallax in Table 2), and color. These advocates for both VRISE intersecting based on individual, hardware, and software characteristics.

3.2.3.4 Visual fatigue is not a sub-symptom of cybersickness

Wang et al. (2019) show that users can present visual fatigue without reporting visually induced motion sickness. Bando et al. (2012) remind that static stereoscopic images drive visual fatigue and that moving images increase fatigue. Conversely, binocular cues influence perceived motion in VR and can impact vection (Luu et al. 2021b). Active viewing induces higher vection compared to passive viewing. Stereoscopy seems to increase vection by changing optical flow proprieties (Palmisano et al. 2020b). Therefore, visually induced motion and vergence-accommodation conflict play a role in both VRISE. But visual fatigue can occur in VR without visually induced motion sickness. Visual fatigue is not a sub-symptom of cybersickness but an intersecting VRISE.

The following section concentrates on works tackling visual fatigue when working in VR.

3.2.4 Visual fatigue and working in VR

Visual fatigue is already an issue in everyday work, with various screen uses putting a large population at risk. At least 50% is potentially at risk (Sheppard and Wolffsohn 2018). Near work on computer screens is an issue regarding dry eye, ametropia, and accommodation or vergence mechanisms. Therefore, adding HMDs would increase screen use at the workplace. HMD use seems to drive higher visual fatigue than PC screen, tablet, or smartphone uses (Han et al. 2017; Yu et al. 2018; Souchet et al. 2018; 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 vergence compared to a baseline, whether duration use is 10 or 50 min (Szpak et al. 2020). The Szpak et al. (2020) study took 40 min after VR use for those measures to go back to baseline. However, their study shows that starting after 10 min exposure user's oculomotor functions similarly changed. Several works present the comparable results about how accommodation and vergence are negatively impacted after playing video games (Yoon et al. 2020; Alhassan et al. 2021). However, studies sometimes find contradictory results. There was no decrease in accommodative and vergence functions after 25 min of playing in Munsamy et al. (2020). In other studies, there was an improvement in the amplitude of accommodation after 10 min of use two times a day for two weeks (Long et al. 2020) which could be due to changes to the ciliary muscle. Similar findings by are presented by Mohamed Elias et al. (2019). Interestingly, during video game play for 20 min, blinks seem similarly impacted with HMD and PC, but lipid layer thickness increased more in VR (Marshev et al. 2021).

However, video games in VR findings might not apply to typical tasks of office workers in a VR environment. Eleven studies, including interaction types related to what office work in VR would require from users, detect visual fatigue (see Table 3).

In summary, despite the few works directly tackling VR-induced visual fatigue at work, existing experiments point out that visual fatigue arises with similar interactions and content to what working in VR would require. Volume visualization does not always require stereoscopic images (Laha et al. 2012). By extension, not all work tasks would require stereoscopy. Therefore, stereoscopy use must be used with discretion. Only a few contributions directly investigate visual fatigue in the context of office-like tasks in VR. Dedicated works should better measure, detect, and evaluate visual fatigue induced by HMDs and the consequences on human performance while working in VR. This section shows that visual fatigue is already a concern for general screen uses. VR would generate an extra load on workers' visual systems and, therefore, their well-being. Furthermore, the possible influence of visual fatigue on available memory workload could directly influence work performance in VR (Park et al. 2015; Eckstein et al. 2017; Daniel and Kapoula 2019; Alhusuny et al. 2020; Bernhardt and Poltavski 2021; Souchet et al. 2021b).

3.3 Muscle fatigue and musculoskeletal discomfort

3.3.1 Muscle fatigue and musculoskeletal discomfort overview

According to Gandevia (2001), muscle fatigue is defined as an "*exercise-induced reduction in the ability of a muscle or muscle group to generate maximal force or power.*" This leads to difficulty performing a voluntary task (Gruet et al. 2013; Taylor et al. 2016). Muscle fatigue mainly refers to intense exercises like sports or physically demanding work (Wan et al. 2017) (e.g., prolonged standing Halim et al. 2012; Coenen et al. 2018)) but also screen work (Coenen et al. 2019)). 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 (Eltayeb et al. 2009; Calik et al. 2020; Heidarimoghadam et al. 2020; Frutiger and Borotkanics 2021). Despite some short-term physical discomfort, musculoskeletal disorders appear temporarily. After a few minutes of rest, users recover from muscle fatigue (Sesboüé and Guincestre 2006). On the other hand, 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 hands are not the only interaction modality in VR. The head is widely exploited (Monteiro et al. 2021). Similar to visual fatigue, computer, and office work already raised the issue of musculoskeletal discomfort, and VR could add to physical load (Reenen et al. 2008; Waongenngarm et al. 2020).

3.3.2 Muscle fatigue and musculoskeletal discomfort occurrence

In VR, users are interacting with a computer-generated virtual environment. The stimuli, inputs from users, and feedback depend primarily on HMDs. Then, depending on the interaction modalities, a user can use controllers, their hands, their head, their eyes, and other body movements to induce changes in this virtual environment (Rogers et al. 2019; Kim et al. 2020; Monteiro et al. 2021; Vergari et al. 2021). 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 habit and can lead to muscle fatigue.

Table 3 Visual fatigue detected with HMD use depending on tasks comparable to office work in VR (video games that require interactions or stimuli too far from office-like tasks in VR have been excluded)

Reference	Task	Effects on the visual system	Duration (min.)	HMD
Souchet et al. (2018, 2021a, b)	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
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. (2019a, b)	Watching 2D videos	Blink ratio in the constant speed disparity changes group is higher	60	HTC Vive + aSee Pro VR eye tracker
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
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 + Eye tracking
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
Chen and Hou (2021)	Teleporting to the target position and using ray-casting to select the target sphere	Total blink duration, average blink duration, and variance of blink duration increase. Number of fixations, total fixation duration, average fixation duration, and variance of fixation duration decrease. Pupil diameter remain stable	From 20 to 30	HTC Vive Pro Eye

Table 4 Possible factors inducing muscle fatigue and musculoskeletal discomfort in VR

Individual	Hardware	Software
Age	HMD 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
		General posture and body rotation
		Sitting or standing
		Body parts representation and feedback (avatar)

Since physical load varies heavily depending on the work context, we directly focus on VR-related factors. In Table 4, we summarized factors identified in 11 contributions regarding muscle fatigue and musculoskeletal discomfort while using VR (Chihara and Seo 2018; Kim and Shin 2018; Lee and Han 2018; Dube and Arif 2019; Song et al. 2019; Yan et al. 2019; Bourdin et al. 2019; Kartick et al. 2020; Li et al. 2020b, a; Penumudi et al. 2020).

Other possible factors might influence muscle fatigue and musculoskeletal discomfort, but that have yet to be further tested in the VR context (therefore, we did not list them in Table 4), including the following:

- Cognitive exertion has a negative effect on subsequent physical performance (Brown et al. 2020).
- Depending on environmental illumination and screen brightness (PC), workers might compensate with postural changes, influencing muscle fatigue (Merbah et al. 2020).
- Stress could promote muscle fatigue (Dehdashti et al. 2017).

Contributions we 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.

3.3.3 Muscle fatigue, musculoskeletal discomfort, and working in VR

During the late 1990s, Nichols (1999) had already identified muscle fatigue or musculoskeletal discomfort issues. Sixteen articles met inclusion/exclusion criteria.

E. Kim and Shin (2018) compared keyboard and mouse document editing tasks on a computer with an HTC Vive. The authors show that HMD has higher physical stress because of weight and lower resolution (reading text). VR text-entry requires more contributions causing muscle fatigue (Dube and Arif 2019). The weight of HMDs themselves could be a source of discomfort (Yan et al. 2019) as users' neck joint torque is affected and the optimal center of mass position of HMDs is varying depending on users' postures (Chihara and Seo 2018; Ito et al. 2019; Sun et al. 2019). HMD weight can be perceived as higher by users the lower the number of belts (Song et al. 2019). The physical tension on the neck can change with an increased number of belts distributing the weight. According to Penumudi et al. (2020), shoulder flexion angle, neck flexion moment, and muscle activities of the neck and shoulder are excessive with vertical target locations when interacting with targets at several angles in the 3D environment. Interaction gestures play a role depending on their amplitude. This can lead to musculoskeletal discomfort, so some contributions develop microgestures (Li et al. 2020a). However, depending on the tasks in the virtual environment, involving more of the body can be necessary (Kartick et al. 2020). When comparing the same real gestures versus VR gestures (CAVE), Ahmed et al. (2017) showed that physical fatigue is higher in VR. Bourdin et al. (2019) showed that modifying postural/gesture feedbacks of users' avatar in VR drive unconscious motor and muscular adjustments. Time seems a factor to consider when watching VR videos as it provokes erector spinae and upper trapezius muscles fatigue (Lee and Han 2018). Conversely, watching 360° videos, despite more neck movements, seems to lead to less fatigue than traditional video (ibid.). As little as 15 min in VR for laparoscopic tasks drive users to declare slight physical discomfort (Li et al. 2020b). The arm fatigue issue is inerasably tackled during the design of virtual environments (Evangelista Belo et al. 2021; Iqbal et al. 2021). It indicates that the issue of muscle fatigue is increasingly acknowledged by peers.

In summary, few contributions have considered possible muscle fatigue provoked by state-of-the-art virtual environments and HMDs. Based on such a few previous scientific works, 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, peers and application creators must acknowledge that muscle fatigue could influence use and users' discomfort. However, since VR requires interactions different from computer work, it

Table 5 Possible factors inducing acute stress in VR based on a synthesis of previous works

Individual	Hardware	Software
Age	Techno-stress	Techno-overload
Gender	Apparatus malfunctions	Public speaking
Experience with a real-world task		Task difficulty
Experiences with a simulator (habituation)		Time pressure
History of headaches/migraines		
Body mass index		
Personality traits		
Anxiety and stress prior to VR use		

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).

3.4 Acute stress

3.4.1 Stress overview

Stress is a concept whose definition is not unified in a collective theory (Epel et al. 2018). Revisiting the 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 the human strategy to reallocate energy to reach homeostasis or allostasis in reaction to stress induction, which defines adaptation to maintain equilibrium in the human's systems (Ganzel et al. 2010; Dewe et al. 2012; Asarian et al. 2012; Ramsay and Woods 2014; Boucher and Plusquellec 2019). The transactional theory of stress (Lazarus and Folkman 1984; Biggs et al. 2017) predicts that stress as a process is transactional. The path from a stressful situation to the outcome is individualized, situationally specific, and inseparable from the cognition of the experience process. To disambiguate our interpretation of stress (Bienertova-Vasku et al. 2020), we consider stress as a negatively perceived factor or situation (psychology). Three components define stress (Kim and Diamond 2002; Fink 2016): arousal or excitability (Cohen 2011), perceived aversiveness (Kim and Diamond 2002), and uncontrollability (Breier et al. 1987). Stress defines a wide range of human interactions with its environment (Schneiderman et al. 2004). We focus on acute stress provoked by VR at work in our context. Therefore, we describe the acute stress response occurrence hereinafter.

3.4.2 Acute stress occurrence

Acute stress is defined as a sudden or short time stressor (trauma, perceived threat, death of a loved one, job loss, etc.) as opposed 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, etc.) and psychological (novelty, social conflict, unfamiliarity with environment, etc.) (Monroe and Cummins 2015; Monroe and Slavich 2016). With animal models, Li et al. (2019) indicate that the effects of physical stress appear early but are relatively moderate. In contrast, the effects of psychological stress appear late but are more severe. However, with humans, physical and psychological stress could interact and accumulate (Abdelall et al. 2020). Acute stress responses occur within seconds to several hours (Godoy et al., 2018; Shields et al., 2017). There are individual differences in how people respond and cope to stressors (Dewe 2017; Stephenson and DeLongis 2020).

Stress at the workplace covers various experiences one can face (Colligan MSW and Higgins 2006). We focus on the acute stress that may be compounded by VR or a new source in office tasks. Acute stress, in general, can impair executive functions (Shields et al. 2016). According to LeBlanc (2009), stress reduces selective attention (Lee and Choo 2013; Bater and Jordan 2020), impairs working memory, enhances memory consolidation (Roesler and McGaugh 2019), and impairs memory recall/retrieval (Staresina and Wimber 2019; Klier et al. 2020). Therefore, we can infer that stress could impair work performance when fulfilling tasks in VR depending on task typologies.

A summary of factors favoring acute stress in the office-like tasks in VR context is proposed in Table 5. Hereafter it is described how acute psychological and physical stress can be induced at the workplace when using VR. As little literature about time pressure and task difficulty in VR regarding stress has been found, those factors are presented in the last section about mental overload as they also seem to influence it.

3.4.3 Acute stress and working in VR

One study assessing stress in VR office linked to the apparatus and three public speaking induced-stress (Trier Social Stress Test corresponding to presenting during a meeting) articles met inclusion/exclusion criteria.

3.4.3.1 Techno-stress provoked by VR Growing information and communication technology (ICT) use at the workplace induces a specific type of stress factor: techno-stress (Brivio et al. 2018; La Torre et al. 2019). Techno-stress refers to an IT user's experience of stress when using technologies (Ragu-Nathan et al. 2008). It has been observed with the introduction of many ICTs in the workplace (Tarafdar et al. 2015; Wang et al. 2020; Karimikia et al. 2020). Techno-stress can lie on the Transactional Theory of Stress (Zhao et al. 2020) presented 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 ICT, which drives employees to feel that their computer skills are inadequate. Symptoms include poor concentration, irritability, memory disturbances, and exhaustion. Since VR is new for most workers, it is reasonable to presume it could lead to techno-complexity stress. Workers will have to constantly learn how to use this ICT (Tarafdar et al. 2019). VR might replace a part of existing ICTs. However, it might add to and result in techno-overload, which is simultaneous, different streams of information that increase the pace and volume of work (Atanasoff and Venable 2017).

Inside this techno-overload, the "information overload" dimension (Nisafani et al. 2020) could apply in data analyses in VR, for instance. Since VR is new for most workers and implies side effects, we can predict high psychological and physiological demands (Atanasoff and 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 a stress response similar to other apparatuses (Weinert et al. 2020; Dragano and Lunau 2020; Tarafdar et al. 2020). The dynamic to have workers in a virtual office can facilitate such techno-stress (Stich 2020). Ultimately, techno-stress could negatively impact general and task performance (Tams et al. 2018; Nisafani et al. 2020).

In summary, techno-complexity is critical as it could make VR perceived as non-efficient to fulfill tasks. It could impact task performance itself, and VR could be an additional stress source that negatively impacts workers' well-being.

3.4.3.2 Public speaking-induced stress in VR meetings Meetings in VR are one popular use case at work. During those meetings, workers need to speak in public. Depending on the worker, one can suffer from public speaking anxiety, common in the general population (Ebrahimi et al. 2019; Marcel 2019; Gallego et al. 2021). Public speaking is well known to induce acute stress, even in healthy adults without public speaking anxiety. This is why the Trier social stress test (TSST) is used 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 (Zimmer et al. 2019; Helminen et al. 2019). Audience feedback in VR seems to impact stress (Barreda-Ángeles et al. 2020). Hence, it could mean that VR induces higher stress during meetings requiring workers to do presentations.

In summary, public speaking could induce higher stress in VR compared to PC. Therefore, it should be considered a stressor that can affect workers even in VR.

3.5 Mental overload

3.5.1 Mental workload overview

Cognitive load and mental workload are often used as synonyms in the literature (Van Acker et al. 2018). The cognitive load concept is used in the learning field, while the mental workload is used in ergonomics / human factors (Orru and 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 (Camina and Güell 2017; Chai et al. 2018; Adams et al. 2018). According to 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. Working memory resources are 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 (Basil 2012).

Van Acker et al. (2018) indicate that 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. Numerous theories of mental workload compete and ad hoc definitions and frameworks are proposed in the literature (Lim et al. 2013; Dehais et al. 2020; Vanneste et al. 2020). Synthetizing 82 previous works, Van Acker et al. (2018) propose an explanatory framework of mental workload. This framework by Van Acker et al. (2018) gathered common predictive components of mental workload in work-related tasks at an occupational level. We concentrate on how working memory can be overloaded, impacting task performances, quality, and completion times (work-related in Van Acker et al. (2018) framework). Mental workload depends on cognitive work demands (Causse et al. 2017) and resource consumption. Two demands are often referenced: time pressure and task difficulty/complexity (Galy et al. 2012). However, time pressure is not listed in Acker et al.'s (2018) framework.

3.5.2 Mental overload occurrence

Depending on task characteristics, workers can face suboptimal levels of mental workload, both underload, and overload. M. S. Young et al. (2015) indicate that overload occurs 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. The most commonly accepted hypothesis describes the relationship between mental workload and performance through an ‘‘inverted U-shape,” which is disputed (Babiloni 2019). M. S. Young et al. (2015) propose an updated representation of relationships between performance, task demands, and resource supply. High task demand, thus increasing resource demand, does not constantly negatively impact performance. Peers rarely concentrate on mental underload as the concept is difficult to define and explain correctly (Young et al. 2015; Sharples 2019). Mental workload is also dependent on attention (Curtin and Ayaz 2019; Sepp et al. 2019) or engagement (Dehais et al. 2020).

Zimmerman (2017) defines task load as a measurement of human performance that broadly refers to the levels of difficulty individual encounters when executing a task. Multitasking can negatively impact task performance (Modi et al. 2020). Stress and task difficulty impact cognition (Kim et al. 2017). Depending on the level of mental workload (dependent time pressure and task difficulty (Galy et al. 2012)), stress, and despite a link between difficulty and repetition rate, difficulty may either enhance task performance or decrease it (Song et al. 2011; Main et al. 2017). De Dreu et al. (2019) showed that high task difficulty leads to lower performance and higher response times. Using VR rather than classical paper-and-pencil or computerized measures to perform neuropsychological assessments revealed increased complexity and difficulty, suggesting that VR requires additional cognitive resources (Neguţ et al. 2016). Interestingly, Neguţ et al. observed that the most substantial effect is measured with healthy participants (compared to clinical participants).

Denovan and Dagnall (2019) define time pressure as insufficient time to complete necessary tasks. This insufficient time available is an individual perception of the amount of time necessary to fulfill a task (Ordóñez et al. 2015). It is a challenging stressor that can be coped via extra efforts, leading to strain and exhaustion (Prem et al. 2018). Caviola et al. (2017) show that solving complex math problems under time pressure fosters strategies that can be applied rapidly but negatively impact task performance. Time pressure can be a stressor that impairs performances, but less so with procedural tasks (McCoy et al. 2014; Prasad et al. 2020). The more time for a task, the less stress (Heikoop et al. 2017). The surgery literature informs us that time pressure negatively impacts performances (Arora et al. 2010) and decision-making (Modi et al. 2020).

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 intrinsic task load, users’ characteristics, feedback, and coping strategies depending on the task, which ultimately impacts performance.

3.5.3 Mental overload and working in VR

Scientific knowledge regarding a VR office, especially the possible mental workload consequence, seems rare. Other contexts, close to typical tasks performed in such virtual environments, are presented hereafter. Table 6 summarizes twenty-one studies that analyzed mental workload in VR with office-like tasks. Four of the following studies compare PC to VR (Zhang et al. 2017; Broucke and Deligiannis 2019; Makransky et al. 2019; Tian et al. 2021), which is relevant in our use-case scenarios as we focus on replacing current tasks completed on a PC by VR. Contradictory results regarding mental workload are observed. Filho et al. (2018) directly investigate office-like task issues by creating “VirtualDesk,” consisting of data visualization and analytics. Mental workload appears similar in VR to PC. However, VR presents a lower mental workload for geo-visualization and trajectory data exploration than PC (Filho et al. 2018, 2019, 2020). But, Shen et al. (2019a) report that tasks in a virtual environment versus a real office drive higher mental fatigue. 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 et al. 2018b; Zielasko et al. 2019; Biener et al. 2020; Gao et al. 2021; 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 impact mental workload, e.g., text input posture and required movement (Knierim et al. 2018; Speicher et al. 2018a).

The literature that assesses mental workload in VR is still scarce. Therefore, it would be inappropriate to generalize the present results to all workplace tasks context. 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 (Filho et al. 2018, 2020; Wismer et al. 2018; Broucke and Deligiannis 2019; Armougum et al. 2019). On the other side, VR seems to lead

Table 6 VR impacts on mental workload depending on tasks that are comparable to what working in VR would require from users (video games that require interactions or stimuli too far from office-like tasks in VR have been excluded)

Reference	Task	Mental workload impacts	HMD
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 leads to higher mental workload than physical simulation	Oculus rift
Broucke and 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 leads to higher mental workload (and a decrease in knowledge acquisition) compared to PC	Samsung GearVR with Samsung Galaxy 6
Shen et al. (2019a, b)	1) 40-min typo modification task, Psychomotor Vigilance Task (PVT), 30-min rest; 2) 40-min search of pictures in a folder, related to keywords, PVT, 30-min rest; 3) 40-min text entry, PVT, 30-min rest; 4) 40-min image classification, PVT, 30-min rest; 5) PVT	Mental fatigue is higher with in VR compared to a PC	HTC Vive
Biener et al. (2020)	Content transfer task and Puzzle task with different interaction metaphors and interfaces	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 Content transfer: Gaze-based interaction faster than bimanual with similar performances. Gaze-based interaction shows a lower mental workload than bimanual	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

Table 6 (continued)

Reference	Task	Mental workload impacts	HMD
Filho et al. (2020)	Geo-visualization and Trajectory Data Exploration (Space–Time Cube)	VR leads 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 fulfill 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 requiring 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
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

to mental overload with tasks not requiring such spatialization cues or interactions when those interactions are too far from what users are accustomed to as well (Wismer et al. 2018; Bernard et al. 2019; Baceviciute et al. 2021). Those results seem moderated by expertise within VR and the task demands (Aksoy et al. 2019; Luong et al. 2019; Armougum et al. 2019). For instance, outside of VR, when time and load on the resources are high, humans hit the maximum resource allocation capacity (McGregor et al. 2021).

4 Discussion and limitations

4.1 Cybersickness and working in VR

Most paradigms to study cybersickness (visually induced motion sickness) are games, driving tasks, or videos inducing a lot of movements to ensure that symptoms will occur (rollercoaster, multiple head movements, walking in VR, etc.). However, those paradigms represent little of the office work experience. We summarized ten previous works tackling cybersickness with work tasks (Zielasko et al. 2017, 2019; Lages and Bowman 2018; Andersen et al. 2019; Guo et al. 2019a; Coburn et al. 2020; Boges et al. 2020; Filho et al. 2018, 2019, 2020). Locomotion type heavily influences cybersickness in those experiments. It appears that sitting and avoiding too many movements in the virtual environment would reduce the chances for workers to present cybersickness symptoms. Ultimately, generalizing VR use when part of the population is at risk of side effects could, in the future, become a form of discrimination for potential workers (Stanney et al. 2020b). Fifty different factors could induce cybersickness (Rebenitsch and Owen 2021). During experiments with VR, more than 15% of participants are susceptible to dropout because of VR side effects (Saredakis et al. 2020). This implies that part of the workers might not even maintain application use. Thus, cybersickness can negatively impact VR adoption at the workplace.

4.2 Visual fatigue and working in VR

Few contributions regarding visual fatigue and the vergence-accommodation conflict in VR are available to date in the work context. Visual fatigue is already an issue in everyday work with various screen uses as at least 50% of the population is at risk (Sheppard and Wolffsohn 2018). Adding HMDs could increase screen use at work, and it seems that HMDs drive toward higher visual fatigue than PC, tablet, or smartphone uses (Han et al. 2017; Yu et al. 2018; Souchet et al. 2018; Zhang et al. 2020). The vergence-accommodation issue arises when displaying stereoscopy. Therefore, not displaying stereoscopy unless it is beneficial to task completion should be considered. However, the optical proprieties of HMDs and other variables of virtual environments themselves could influence visual fatigue. Updating Bando et al. (2012) list, we identify fifteen possible factors that could induce visual fatigue in VR. Furthermore, a possible influence of visual fatigue on available memory workload could directly influence work performance in VR (Park et al. 2015; Eckstein et al. 2017; Daniel and Kapoula 2019; Alhusuny et al. 2020; Bernhardt and Poltavski 2021). We reviewed eleven experiments with stimuli or tasks that could apply to the work (Souchet et al. 2018, 2019, 2021a; Shen et al. 2019b; Hirota et al. 2019; Jacobs et al. 2019; Iskander et al. 2019; Wang et al. 2019; Thai et al. 2020; Yoon et al. 2020; Chen and Hou 2021). Those studies mostly show the impacts of VR on accommodation and vergence during and after use. The mean duration of immersion in the ten reviewed studies was 26.22 min. Therefore, immersion of about 26 min or more is likely to induce visual fatigue.

4.3 Muscle fatigue, musculoskeletal discomfort, and working in VR

Like any human–computer interaction situation, VR could lead to repetitive strain injury (van Tulder et al. 2007). Therefore, peers and application creators must acknowledge how muscle fatigue could influence use and users' discomfort. Conversely, VR could also be a way to induce task variation at the job level, which might help alleviate general musculoskeletal discomfort (Luger et al. 2014). Therefore, it is unclear how significant muscle fatigue can be with VR use. Previous studies show negative impacts on.

- Users’ neck joint torque
- Stress on the neck and shoulders
- Flexion angle, neck flexion moment, muscle activities changes
- Excessive vertical target locations
- Arm fatigue

More experiments are needed to encompass VR risks regarding muscle fatigue.

4.4 Acute stress and working in VR

Stressful work tasks are particular to individuals and situations. Introducing VR as a new ICT tool can lead to additional stress. Encompassing every factor is too complex. We chose to concentrate on techno-stress (with techno-complexity and techno-overload, which directly related to the user experience of the hardware and software), public speaking, task difficulty, and time pressure. Four articles met our criteria. In the short term, these stressors could negatively influence work performances and use performances in VR since stress impacts cognitive resources. However, it is unclear how those stress factors arise in VR compared to PC.

4.5 Mental overload and working in VR

Introducing virtual reality as a new ICT tool implies changing interactions and interfaces. Therefore, expertise with VR and new ways of fulfilling tasks could impact mental workload. The interaction and interface could lead to mental overload if they require higher working memory resources. It appears that typical tasks transposed to VR do require more working memory resources, and this includes 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 take advantage of VR because of these spatial information possibilities. VR and its effects on mental workload lack contributions directly assessing work tasks. Looking at assimilable tasks, VR impacts on mental workload are mixed and sometimes contradictory. Consistent findings are that mental workload in VR seems higher than other apparatuses. However, this does not always negatively impact task performance.

Furthermore, workers' expertise in both VR and tasks influence performance and objective and subjective mental workload. Poor or inadequate interaction metaphors and interfaces could lead to mental overload and decreased task performance. Furthermore, workers could put VR aside when high time pressures and task loads require high performance if VR provokes mental overload. However, at the time of this narrative review, little scientific data can generalize those predictions. Possible working memory resource saturation is provoked by cybersickness, visual fatigue (Mittelstaedt et al. 2019; Mittelstaedt 2020; Park et al. 2021), and acute stress (Epps 2018; Collins et al. 2019; Borghini et al. 2020; Wulvik et al. 2020) should also be considered. This could impact the total amount of available mental resources and reduce the user’s ability to allocate sufficient resources to tasks in VR.

4.6 Limitations of the present review

This narrative review is more summative and less detailed than the results of a formal methodology review (Pautasso 2013; Stratton 2016) with more narrowed keywords, publication date range, and inclusion and exclusion criteria. The motivation was to gather information usually scattered in various articles within multiple fields. This allowed for a review of five different VRISE. We concentrated on typical office-like tasks. Due to the primary uses of VR for video games (entertainment in general) and training, part of the presented articles may not directly relate to virtual environments for work. However, our contribution is one of the first to address VR ergonomic risks when introduced in the workplace. Hence, part of described factors and VRISE at work are speculative based on previous works.

4.7 General discussion

We extend the Chen et al. (2021) review despite the above-mentioned limitations. Our work gives a unique insight into the current and possible future issues in introducing VR at work following Stanney et al. (2020b). Stanney et al. focused on cybersickness. Here, we differentiate cybersickness from visual fatigue to better represent VRISE and VR ergonomic risks in general. Furthermore, we orientated our review to directly summarize findings from experiments using stimuli close to tasks an office worker could fulfill to be more focused. By treating five VRISE risks, we also show that the current contributions' focus on cybersickness is necessary but should not consume all peers' efforts. Indeed, other concerns regarding visual fatigue, muscle fatigue, acute stress, and mental overload require further study.

Furthermore, cybersickness is a portmanteau word that often leads to cloudy VRISE and other VR side-effect explanations. Cybersickness should not be used to encompass all VRISE. Peers abundantly tackled cybersickness within the past three years (Gallagher and Ferrè 2018; Nesbitt and Nalivaiko 2018; Weech et al. 2018; Descheneaux et al. 2020; Chang et al. 2020; Saredakis et al. 2020; Stanney et al. 2020b; Grassini and Laumann 2021; Howard and Van Zandt 2021; Rebenitsch and Owen 2021). The uncertainty around this concept is partly due to theoretical challenges and the widely varying VR environments. Immersing a human being in a computer-generated environment induces various modifications compared to their real environment. Although a general concept of VR side effects is tempting, this may imply too many variables to consider. Human perception, cognition, and action are large research fields, independently of VR. Therefore, the cybersickness concept should be used when talking about visually induced motion sickness but not encompass all symptoms that occur in VR. Hence, despite the shortcomings of a narrative review, this allowed us to go over the concept of "cybersickness" to clarify the "VRISE" one and add other side effects that are task-related (acute stress and mental overload).

By cross comparing literature, we showed part of the variety of VRISE risks. Furthermore, to the best of our knowledge, the present review is the first to formally treat sensorimotor mismatch and psychological risks of VR in the same paper. We reproduced Rebenitsch and Owen's (2021) list of factors that could induce cybersickness and extended the logic to visual and muscle fatigue. We relied on existing models listing factors not developed directly with VR for acute stress and mental overload. Thanks to this method, we can see that various factors could influence cybersickness, visual fatigue, muscle fatigue, acute stress, and mental overload in VR. Sometimes those possible factors are listed for each side effect, leading one to consider possible interactions between those states. When using cybersickness list of factors and comparing it to the other four VRISE (see supplementary materials), we identify that 31 out of 50 factors are similar among all VRISE although not always using the same terminology. The duration factor is present in all five VRISE, age and scene content or scene complexity in four VRISE, position tracking error, the ratio of virtual to real world in and body mass index in three VRISE.

Moreover, it allows identifying possible interactions between those five side effects. Interactions are not directly treated in this paper, but there are growing advocates for them (Park et al. 2015; Iskander et al. 2018; Alsuraykh et al. 2019; Mittelstaedt et al. 2019; Parent et al. 2019; Alhusuny et al. 2020). Those interactions are issues implying difficulties when characterizing what is measured when assessing VR side effects, particularly with complex stimuli.

4.8 Proposal of a research agenda regarding VRISE risks at work

Immersing humans in VR mobilizes several sensorimotor stimulations. In current HMDs, this mainly constitutes visual, vestibular, and proprioceptive systems. The existing scientific literature draws guidelines to identify and reduce VR ergonomic risks. However, it should be clear to potential VR users and creators that, to date, no existing method can fully alleviate VR side effects. Therefore, scientific and industrial contributions are still needed to better consider VR ergonomic risks and human factors. The EU-OSHA already identified these issues (EU-OSHA 2019). Therefore, we can reasonably imagine that regulation and legislation regarding VR use at work shall emanate from the EU and other governmental agencies. In their present form, HMDs and virtual environments have issues complying with workers' safety and health, fulfilling office-like tasks. Stanney et al. (2020b) provide an R&D agenda to resolve cybersickness. Most actions they list are estimated to happen within one to five years when their work has been published. This is an optimistic agenda. Even if only focused on cybersickness, the phenomenon's complexity could take longer to check most of the listed actions. Like we have seen with cybersickness and visual fatigue, conceptual issues are at stake. VRISE is a broad term encompassing many factors and the possible relationship between side effects should be considered. Based on our review of VR side effects, it is clear that robust methods to monitor cybersickness, visual fatigue, and muscle fatigue require more scientific contributions. Furthermore, no theory predicting VR side effects makes consensus, and peers require more experimental work. This can apply to visual fatigue, muscle fatigue, acute stress, and mental overload in VR. Therefore, Table 7 lists a research agenda.

Table 7 Agenda proposal to inventory VR ergonomic risks at work

Focus	Research issue	Current status
Theoretical	Reaching consensus on cybersickness theory based on new experimental proofs by reducing predictions to visually-induced motion	Four competing theories are supported with an inclination for Sensory cue conflict
Theoretical	Clarifying differences between cybersickness and visual fatigue	Symptomology is partly similar which make unclear what symptoms are visual fatigue or cybersickness related
Theoretical	Modeling probable tangles between cybersickness, visual fatigue, muscle fatigue, acute stress and mental overload	Most researches about VR side effects consider one at a time to remain focus. However, other side effects that might influence or be alternative explanations for obtain results are rarely treated
Experimental	Testing cybersickness's competing theories on common grounds stimuli	Experimental paradigms are too heterogeneous, rarely using stimuli relevant for work, and it makes difficult to discuss cybersickness based on common grounds
Experimental	Measuring visual fatigue during and after VR use with physiological sensors (ECG, EDA, Eye tracker)	Most contributions use video games and showed negative impacts on accommodation and vergence
Experimental	Identifying interactions and interfaces for office-like tasks to banish for reducing muscle fatigue	With new input devices (natural gestures…) interactions and interfaces can evenly impact muscle fatigue and the best ones to reduce it are increasingly tested
Experimental	Measuring cybersickness with up to date questionnaires and physiological sensors	Contribution start to use physiological sensors and new questionnaires but a lot are still using only outdated questionnaires
Experimental	Measuring acute stress induced by context, tasks and HMDs	Stress is complex, introducing HMDs could contribute to techno-stress and depending on tasks and context, VR could favorise stress
Experimental	Measuring cybersickness, visual fatigue, muscle fatigue, acute stress and mental overload in the same experiments with physiological sensors to distinguish psycho-physiological variations in VR	Most experiments only tackle one ergonomic risk at a time, it virtually eliminates alternative explanations about what is measured with physiological sensors
Experimental	Creating a monitoring toolkit to diagnosis VR side effects while users are immersed in lab and at work	Contributions assessing "automatically" cybersickness and stress in VR exist but rarely with work tasks, other ergonomic risks could be better considered as they could influence diagnosis

We should be parsimonious with the introduction of VR at work. Increasing scientific works are prompt to point out the benefits of HMDs. However, they often do not mention risks. Our narrative review concentrated on ergonomic risks, which could directly impact workers' safety and health. We do not have enough data on the introduction of VR for a large part of office workers. VR has been used in specific industries like automotive, design, or aviation, for pilot training purposes. In those cases, benefits (economic or task risk reduction) seem to surpass ergonomic risks. However, similar benefits still need to be determined for office-like tasks. Workers' performance, health, and safety are at stake.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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