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REVIEW

Measuring Visual Fatigue and Cognitive Load via Eye Tracking while Learning with Virtual Reality Head-Mounted Displays: A Review

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ABSTRACT
Virtual Reality Head-Mounted Displays (HMDs) reached the consumer market and are used for learning purposes. Risks regarding visual fatigue and high cognitive load arise while using HMDs. These risks could impact learning efficiency. Visual fatigue and cognitive load can be measured with eye tracking, a technique that is progressively implemented in HMDs. Thus, we investigate how to assess visual fatigue and cognitive load via eye tracking. We conducted this review based on five research questions. We first described visual fatigue and possible cognitive overload while learning with HMDs. The review indicates that visual fatigue can be measured with blinks and cognitive load with pupil diameter based on thirty-seven included papers. Yet, distinguishing visual fatigue from cognitive load with such measures is challenging due to possible links between them. Despite measure interpretation issues, eye tracking is promising for live assessment. More researches are needed to make data interpretation more robust and document human factor risks when learning with HMDs.

1. Introduction

A new generation of Virtual Reality Head-Mounted Displays (HMDs) is reaching the consumer and corporate markets since 2015 (Yang et al., 2019). Learning appears to be one of the fast-growing applications of HMDs (Arnaldi et al., 2018). These devices usually display stereoscopic (S3D) images (Banks et al., 2012; Reichelt et al., 2010). Exposure to these images can cause visual fatigue (Bando et al., 2012; Matsuura, 2019; Ukai & Howarth, 2008). Visual fatigue is traditionally analyzed as a perceptual phenomenon but rarely as a cognitive phenomenon. However, recent contributions from brain imaging indicate that visual fatigue is characterized by corticosteroid activities like cognitive load (Cai et al., 2017; Chen et al., 2017; Chen & Epps, 2014; Daniel & Kapoula, 2019; Terzic & Hansard, 2017). Eye tracking allows collecting several features that are similarly used to investigate both visual fatigue (Park & Mun, 2015) and cognitive load (Anmarkrud et al., 2019). Therefore, what measures characterize cognitive load or visual fatigue during Immersive Virtual Reality (VR) exposure needs to be clarified. This clarification is specifically necessary for the learning context (Biggs et al., 2018), where learners must not suffer from any cognitive overload or visual fatigue. Such overload and fatigue could potentially reduce their ability to perform learning tasks. Therefore, it is crucial to better measure and understand stereoscopy-induced visual fatigue during the VR learning experience to distinguish it from cognitive load.

This article is a review. Our general purpose is to consider VR as a learning medium through the statement of Robert J. Stone: "*human first, technology second*" (Stone, 2016). Many human factors issues arise with HMDs and are usually treated under the portmanteau word cybersickness, in which visual fatigue is only treated as a symptom of visually induced motion sickness (Chang et al., 2020; Descheneaux et al., 2020; Nesbitt & Nalivaiko, 2018; Rebenitsch & Owen, 2021). Here, we focus on two side effects of VR for learning: cognitive overload and visual fatigue. The targeted audience is both researchers and practitioners/companies willing to use HMDs for learning purposes and assessing learners' visual fatigue or cognitive load live.

The primary purpose is to document risks of visual fatigue and cognitive overload when learning in VR. But HMDs are considered not only for learning but also for daily uses in the medical sector, e.g., see: (Carl et al., 2019; Chan et al., 2018; Fodor et al., 2018; Gilboa et al., 2018; Lindner et al., 2019; Olmos-Raya et al., 2018). In these examples, VR is used with populations potentially more sensitive to side effects due to their pathologies. Despite a growing literature, human factors around HMDs need to be better known. In most use cases, risks are rarely considered, and visual fatigue is absent of some reviews about immersive technologies even though they intend to treat side effects, e.g.: (Suh & Prophet, 2018). Overviews about learning and training in VR only mention cybersickness risks or don't treat VR side effects (Guedes et al., 2019;

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Howard & Gutworth, 2020; Portelli et al., 2020; Zhao et al., 2021). Applications of VR and its side effects are usually considered in separate literature. This spread prevents the use of HMDs for learning purposes with a risk-benefit ratio approach. To fully consider the side effects, they need to be measured in ecological experiments using VR. Such an approach could benefit any other VR applications. In this context, eye tracking is a promising technique to assess part of the risks.

The secondary purpose is to identify which metrics to use for assessing visual fatigue and cognitive load via eye tracking in HMDs. It would help normalize experimental methods in a learning context, which could allow robust systematic reviews and meta-analysis around HMDs for learning purposes in the future as there is legitimate questioning of digital tools used in this specific field (Spitzer, 2014). Yet, this review leads us to point out that distinguishing visual fatigue from cognitive load measured via eye tracking is challenging. To conclude this review, we propose a research agenda to investigate the open questions further and support a robust analysis of the collected data.

2. Background

2.1. Cognitive load overview

Cognitive load is the amount of working memory resources that are used (Leppink, 2017). These working memory resources are limited (Adams et al., 2018; Camina & Güell, 2017; Chai et al., 2018). Cognitive load theory has been mainly developed to design learning instructions while work-related tasks use the mental workload concept (Van Acker et al., 2018). According to Sweller, there are three types of cognitive loads (Sweller, 2016):

- Intrinsic. It corresponds to the complexity of the acquired knowledge, without a reference to how it is presented and acquired;
- Extrinsic. It defines how information is presented and acquired;
- Germane. It defines knowledge integration in long-term memory.

The cognitive load theory has unified many scientific contributions but is criticized (Moreno, 2010). Critics point to the lack of clarity and distinction between cognitive load types (De Jong, 2010). The "germane" load is at the center of these critics. In theory, when intrinsic and extrinsic resources are overloaded, learners focus on the learning process in relation to the learning material (the theme) rather than knowledge (the specific elements to memorize). This makes it almost impossible to distinguish between intrinsic and germane loads. Despite the critic of germane load, cognitive load theory is widely used in researches about learning. Yet, cognitive fatigue is also employed to qualify similar cognitive states than cognitive overload from the cognitive load theory. According to Dobryakova et al. (2013), cognitive fatigue is an inability to maintain cognitive performance due to mental exhaustion. Performance is lower or more variable in relation to an individual's optimal abilities (Holtzer et al., 2010). According to Van Der Linden (2011), cognitive fatigue is temporary in nature, and the optimal abilities can be recovered: e.g., by changing tasks. Therefore, we note that cognitive fatigue is globally describing similar "conditions" to cognitive overload.

Despite conceptual and scientific challenges, cognitive load theory is refutable and evolving (Orru & Longo, 2019). It is commonly used in learning psychology, which is our focus. Therefore, we decided to refer to this theory in the present review. Trying to measure cognitive load while learning, especially to apprehend VR possible side effects, is legitimate. The following section shows that some contributions already document VR impacts on cognitive load while learning. But they are still rare.

2.2. Cognitive load and Virtual Reality while Learning

In a report published in 2018 for the Office of Naval Research (USA), Biggs et al. pointed the lack of study addressing cognitive load issues when learning with VR (Biggs et al., 2018). Our review confirmed this conclusion, and we only found a limited number of articles presented afterward. Only five relevant articles have been included with our criteria. We summarize and comment on those five articles below.

Memorization tasks in VR can be more efficient than on PC if the person can manipulate objects and is represented by a self-avatar (Steed et al., 2016). This is in line with a positive effect on working memory when tasks are mainly related to spatialization (Gabana et al., 2017). However, VR could also saturate working memory while learning because of unnecessary cognitive treatments not related to the learning object (Parong & Mayer, 2018), therefore, adding extrinsic load. Such extrinsic load can be associated with cybersickness that negatively impacts reaction time (Mittelstaedt et al., 2019). The cognitive adaptation effect to VR is pointed out as a possible side effect for learning purposes, but it is not clear how long such effect lasts (Nesbitt et al., 2017).

Two out of five articles presented in this section report positive effects of VR on cognitive load, and three are reporting negative effects. Cognitive load variations seem dependent on tasks, level of interaction required to complete the task (high spatialization or not), users' representation (avatar), and cybersickness. Cybersickness is associated with a negative impact on cognitive load in one included study. Cybersickness is known to induce oculomotor function changes, including visual fatigue (Davis et al., 2014; Rebenitsch & Owen, 2021; Stanney et al., 2020). However, this parameter was not considered in studies when positive impacts of VR on cognitive load had been recorded. Therefore, measuring cybersickness symptoms such as visual fatigue is needed when learning in VR. Visual fatigue alone is a risk, but it could also negatively impact cognitive load. Cognitive load variation while learning needs more scientific contributions. The following section focuses on visual fatigue.

2.3. Visual fatigue overview

According to Evans (2007), visual fatigue or asthenopia generally correspond to eye fatigue and headaches. They are quoting the *American Optometric Association* Sheppard and Wolffsohn (2018) list the symptoms: eyestrain, headaches, blurred vision, dry eyes, and pain in the neck and shoulders. The subjective appreciation of these symptoms is visual discomfort. Visual fatigue is due to a weakness of the eyes or vision, i.e., resulting from a visual or ocular abnormality rather than purely extrinsic (environmental) factors. Lambooij et al. (2009) indicate that visual fatigue is physiological stress resulting from excessive strain on the visual system. Sheppard and Wolffsohn (2018) have reviewed the visual fatigue phenomenon linked to digital uses. They have determined that a large part of the population is at risk. However, they did not evaluate Augmented or Virtual Reality devices nor other devices able to display stereoscopy. Nevertheless, Terzic and Hansard (2017) conduct a review on causes of visual discomfort, which points to future problems with HMDs since they display stereoscopy. The vergence-accommodation conflict induced by stereoscopy (Ukai & Howarth, 2008) in HMDs (Matsuura, 2019; Yuan et al., 2018) is a concern for learning purposes (Biggs et al., 2018). For details about accommodation and vergence mechanisms and conflicts due to stereoscopy, see: (Fuchs, 2017; Hoffman et al., 2008; Jiang et al., 2002; Kim et al., 2014; Leroy, 2016; Mays, 2009; Neveu et al., 2016; Rößing, 2016; Schor, 1992). Studies with the older generation of HMDs measured visual fatigue due to vergence-accommodation conflict (Mon-Williams & Wann, 1998; Mon-Williams et al., 1993; Rushton et al., 1994). A new generation of HMDs still causes visual fatigue (Hirota et al., 2019) and visual discomfort (Cho et al., 2017). HMD users under ecological learning conditions report visual discomfort (Bracq et al., 2019). In the next section, we review visual fatigue's possible impacts on learning while in VR.

2.4. Visual Fatigue and Virtual Reality while learning

Visual fatigue is still a human factor risk when using the new generation of HMDs, specifically if they display stereoscopy (Fuchs, 2017). Yet, very few articles directly assess visual fatigue while learning in VR (Souchet et al., 2019, 2018). Souchet et al. evaluated learning job interviews with a Serious Game with 69 subjects in their first experiment (Souchet et al., 2018) and 59 in the second (Souchet et al., 2019). The learning curves are better for HMD groups (S3D and 2D) than the PC group, although visual fatigue is higher and quality of experience lower than in the PC group. Displaying cyclical stereoscopy provoked higher visual fatigue. The authors conclude that visual fatigue negatively impacts the quality of experience but not learning. However, the virtual environment used requires little depth discrimination and interaction, and the disparity applied to create stereoscopic images for their S3D HMD condition is low. The results might not be the same with high 3D interactions and disparities.

We extended our analyses to other articles than those focussing on learning purposes when assessing visual fatigue. HMDs seem to drive higher visual fatigue than PC, tablet or smartphone uses (Han et al., 2017; Yu et al., 2018; Zhang et al., 2020). Video games show that VR impacts accommodation and convergence compared to a baseline, whether use duration is 10 or 50 minutes (Szpak et al., 2020). In Ancret Szpak et al. (2020) study, it took 40 minutes after VR use for those measures to go back to baseline. However, their study shows that less than 10 minutes did not impact the user's visual system while the duration of 10 and 50 minutes exposure did not change oculomotor functions differently. Comparable results about accommodation and vergence negatively impacted after playing video games are presented in several works (Alhassan et al., 2021; Yoon et al., 2020). However, studies sometimes find contradictory results: no decrease in accommodative and vergence functions after 25 minutes at playing like Munsamy et al. (2020), improvement of the amplitude of accommodation after 10 minutes of use two times a day for two weeks (Long et al., 2020) and similar findings (Mohamed Elias et al., 2019). Usually, studies focus on visual fatigue induced by displayed images: 2D or S3D. When brain activities are measured, task completion inducing visual stress impacts cognition while causing visual fatigue (Kim, Jung, et al., 2011; Kweon et al., 2018; Leigh & Zee, 2015). Therefore, visual fatigue could be an additional burden on learners' working memory resources, lowering their performance. Visual fatigue seems higher with S3D images than 2D images.

It is hard to reconcile these results with the results of Souchet et al. (2018), (2019)), and the main conclusion that can be drawn from this section is that visual fatigue in the context of learning with HMDs still lacks contributions.

2.5. Issues with visual fatigue and mental workload assessment while learning

It appears that both cognitive load and visual fatigue lack scientific contributions in the context of learning in VR. Yet, rare existing studies point to risks of cognitive overload and visual fatigue. Visual fatigue also seems to impact available working memory negatively, although it doesn't always affect learning. However, experimental results are contradictory for the effects of VR on cognitive load. Most experimental paradigms consist of measuring cognitive load and visual fatigue before and after using VR, and live data collection while users are immersed in VR is rare. The reason is that HMDs cover up the visual system, preventing most usual tests, which require access to the visual system. A tool implemented in HMDs to perform live data collection of the visual system behavior would significantly help conduct studies on visual fatigue and cognitive load while learning. Such a tool would allow more contributions better to qualify risks of cognitive overload and visual fatigue.

Several tools are being implemented in HMDs to allow live physiological data collection, such as Electrooculography and Electroencephalography. But both those techniques are susceptible to subjects' movements. In VR, the HMD itself sometimes moves on people's heads, and users also move. Potentially, this implies a lot of artifacts that usual filtering and normalization. Therefore, to that date, eye tracking seems to be more promising and is increasingly implemented in HMDs. We concentrate on eye-tracking in the following section.

2.6. Eye tracking principles

Eye tracking is a technique used to monitor a user's point of gaze and eye motion, e.g., in front of a computer or within a virtual environment (Duchowski, 2017). The advantage is to measure users' gaze location in a scene in real-time (Majaranta & Bulling, 2014) and record visual system behaviors. Video oculography (VOG) (Zemblys & Komogortsev, 2018) is the most democratized technique. VOG consists of gaze location estimation, carried out based on the pupil (the center) tracking and the corneal reflection (of a light emitted on the eye). Often reduced to a portmanteau word, eye tracking also implements pupillometry (Sirois & Brisson, 2014). These techniques have the advantage of being noninvasive and in real-time. But, it involves implementation difficulties (Carter & Luke, 2020; Majaranta & Bulling, 2014). These difficulties are poor accuracy (Dalrymple et al., 2018), loss of tracking, the influence of content (luminance, colors, movements) (Binaee et al., 2016; Goldberg & Wichansky, 2003), and contextual effects related to the apparatus itself (nocebo effect) (Höfler et al., 2018). Furthermore, like any eye tracking technology, the basic assumption is that visual attention is focused on the task that needs to be performed. Therefore, visual attention is supposed not to be somewhere else than the area of interest. Yet, such assumption can be false, therefore limiting the benefits of such technique. Eye tracking also requires high energy consumption, a determining constraint, primarily if implemented in HMDs.

2.7. Considered features to assess cognitive load and visual fatigue via eye tracking

We note that mainly six features are usually used to measure cognitive load (Zagermann et al., 2016) and visual fatigue (J. Iskander et al., 2018). We are presenting them all, notwithstanding the experimental conditions or creators' purpose:

- **Blinks**: this metric has been identified for several years to measure fatigue (Stern et al., 1994). Martins and Carvalho (2015) meta-analysis focuses on blinking as a metric of fatigue (including visual fatigue) and mental load. However, the authors report that at least three environmental factors influence blinking: temperature, relative humidity, and lighting conditions of the room where assessment takes place. The subject's activity during assessment (stimuli, interactions) has also been described to impact the frequency of blinks (Gebrehiwot et al., 2015). According to Lenskiy and Paprocki (2016), a reading task reduces the number of blinks compared to when subjects rest. The movements' velocity in a scene with stereoscopy decreases the number of blinks and visual comfort (Li et al., 2013). This indicates that blinking is attention-related. Simultaneously, blinking has been identified as an indicator of dopamine activity related to cognitive activity in humans as early as five months of age (Bacher et al., 2017).
- **Pupil diameter**: this feature, dilation most often, can be associated with attention and cognitive process (John et al., 2018). However, the environmental variables impacting pupil diameter variation are vast (Peinkhofer et al., 2019): scene colors, brightness, and movement.
- **Fixation frequency**: this feature corresponds to when a gaze fixation stays on a particular object. It is correlated with cognitive load (Zu et al., 2017): fixation time tends to increase with high cognitive load.
- **Point of gaze (POG) accuracy**: this feature relates to the fixation time and represents the distance between the fixed point and a defined target during each fixation. In the event of fatigue, the accuracy of the POG should decrease. This parameter can thus be used to assess visual fatigue (Urvoy et al., 2013).
- **Nystagmus**: this feature is defined as the "*involuntary oscillation movement of the eyeball following disturbance of the coordination of the eye muscles*" (Al-Zubidi et al., 2018). These oscillations increase with visual fatigue and, therefore, can be used to assess visual fatigue.
- **Saccades**: this feature consists of measuring "*quick eye shifts that normally place the line of sight on the desired target in a single smooth movement*" (Schut et al., 2017). Saccades assessment is used to assess visual fatigue (Iatsun et al., 2013) and cognitive load (Zagermann et al., 2016).

These metrics have been used in very heterogenous paradigms, hypotheses, and disciplines. Due to the many variations to be considered for each marker, it is impossible to determine which ones are the most suitable in general. The choice should instead be contextual to experimental hypotheses: e.g., fixation and gaze imply the ability to know what users are looking at depending on the tasks. Therefore, tools able to collect objects of interest are needed. In the following section, we review experimental studies to determine how frequently these features are used. The purpose is to identify recurrent features measured with eye tracking to facilitate reproducibility and compare experimental studies in the future.

2.8. Eye tracking uses examples with VR

Eye tracking is implemented in some HMDs available on the market (Clay et al., 2019). It can be used to monitor the user's visual system for interacting in VR (Luro & Sundstedt, 2019), rendering optimization (NVIDIA Foveated rendering) (Patney et al., 2016), and as an assessment tool of human's physiological state (Charles & Nixon, 2019; Skaramagkas et al., 2021). Eye tracking is also considered to monitor players' behavior in VR (Soler-Dominguez et al., 2017). While learning in VR, eye tracking is considered a psychophysiological assessment tool to replace users' declarations to investigate learning experience (Soler et al., 2017). Eye tracking is also considered to monitor learners' cognitive state (Sonntag et al., 2015), learning curves (Lallé et al., 2015), cognitive load, and visual fatigue (Abdulin et al., 2016; Abdulin & Komogortsev, 2015; Park & Mun, 2015). According to Y. Wang et al. (2018), eye tracking can replace or complete clinical optometric measures. Using eye tracking emerges as a viable solution to measure visual fatigue when using an HMD (Abdulin & Komogortsev, 2015).

Metrics usually collected with eye tracking involve components with high characteristics (recording rate, accuracy). Implementing eye tracking in HMDs implies less expensive components that are less precise (Abdulin et al., 2016). Analytical models corresponding to HMD embedded eye tracking are still in development and tested (Lohr et al., 2016).

Eye tracking is considered for vast uses with HMDs. Technical solutions are growing. Eye tracking can be rationally considered for assessing certain physiological variables. It is considered for assessing visual fatigue, cognitive load, and learning (J. Iskander et al., 2018; Jacob et al., 2018; Krejtz et al., 2018; Zu et al., 2017). However, eye tracking latencies included in HMDs are not equal (Clay et al., 2019; Stein et al., 2021), impacting the quality of feature extraction. How to assess specifically visual fatigue and cognitive load is what we are interested in. The following sections tackle these issues.

3. Review methodology

The research questions (RQ) raised in this article are broad and heterogenous experimental paradigms relying on different scientific disciplines, taxonomies, and communities. Only a very few studies met inclusion/exclusion criteria using eye tracking and HMDs in the learning context. For these reasons, our review is not fully applying the review methodology (Pautasso, 2013; Stratton, 2016). We tried to give a helpful overview that required stepping outside initial inclusion/exclusion criteria (not restricted to HMDs and learning paradigms).

3.1. Research questions, used keywords, searched databases

The research questions and the used keywords to search related articles are listed in Table 1. We searched eight databases. The review is organized following four research questions. It relies on 18 keywords that have been searched solely or combined.

The eight databases queried are Scopus; PubMed; PsycINFO; IEEE Xplore; ACM: Association for Computing Machinery Digital Library; CiteSeerX; arXiv; ERIC: Educational Resource Information Center. We focused on multidisciplinary databases, then psychology and computer sciences. The initial review has been conducted from April to June 2019. An update of the initial findings has been done during the review process in April 2021 to include the latest experiments meeting inclusion/exclusion criteria and increasing the number of considered papers.

3.2. Inclusion and exclusion criteria

We tried to focus on publications since 2009 and experiments combining HMDs and eye tracking. 2015 is the official release date of the Samsung Gear VR on the consumer market. This year corresponds to the first new-generation HMD massively adopted before Oculus Rift (2016 on consumer market). However, a rise of research on S3D is noticeable in the literature around 2010, corresponding to the movie Avatar and TVs displaying stereoscopy (Rotter, 2017).

Articles were **included** if:

- Containing searched keywords in the title or the abstract or keywords
- Published from January 2009 to April 2021

Articles were **excluded** if:

- Focusing on and/or using only Electrooculography (EOG) or Electroencephalography (EEG) for assessing visual system muscular activity in experiments
- Not describing sufficiently material and methods (not presenting stimuli + not presenting display mode, not presenting statistics, not presenting population number) in experiments
- Focusing on non-adult populations and "non-healthy" subjects
- Non-randomized experiments
- Redundant publications

Additional references (i.e., not focusing on the specific researched keywords) are cited for allowing a better understanding of presented and discussed issues. Only a few articles have met inclusion/exclusion criteria. Therefore, to better reflect visual fatigue and cognitive load measures via eye tracker, studies using Computer displays, TV, and other displays are also included.

3.3. Search results

RQ1 and RQ3 include fourteen articles. RQ2 and RQ4 include twenty-two articles. One article is combining RQ1 and RQ2 issues. Therefore, thirty-seven articles are considered. Reviewed papers are marked in the reference list with the symbol "*." These research questions drive us to point to the issue of distinguishing visual fatigue from cognitive load measures via eye tracking (RQ5) through a narrative review.

Table 1. Research questions and searched keywords: ";" corresponds to "OR," "+" corresponds to "AND.".

ID	Research Question	Searched Keywords
RQ1	Which indicator/feature is relevant to measure cognitive load with eye tracking?	Cognitive Load; Cognitive Load Theory; Working Memory; Cognitive fatigue + Eye tracking; Eye Movement
RQ2	Which indicator/feature is relevant to measure visual fatigue with eye tracking?	Visual Fatigue; Eyestrain; Computer Vision Syndrome; Asthenopia; Ocular Fatigue + Eye tracking; Eye Movement
RQ3	What are the experimental results of cognitive load assessment with eye tracking?	Cognitive Load; Cognitive Load Theory; Working Memory; Cognitive fatigue + Eye tracking; Eye Movement
RQ4	What are the experimental results of visual fatigue assessments with eye tracking?	Visual Fatigue; Eyestrain; Computer Vision Syndrome; Asthenopia; Ocular Fatigue + Eye tracking; Eye Movement
RQ5	How can we distinguish visual fatigue from cognitive load?	All search keywords from RQ3 + All search keywords from RQ4

4. Results at assessing cognitive load and visual fatigue with eye tracking

4.1. Features occurrence and description of included studies (RQ1 and RQ2)

The purpose here is to determine the most used features to assess visual fatigue and cognitive load toward the six presented in the previous section. To that end, **thirty-seven studies** met inclusion/exclusion criteria: see Appendix A for full study presentation.

Cognitive load is assessed in fourteen included studies (Appel et al., 2018; Bednarik et al., 2018; Bhavsar et al., 2018; Bækgaard et al., 2019; Daniel & Kapoula, 2019; Das et al., 2020; Duchowski et al., 2018; Hopstaken et al., 2016; Kosch et al., 2018; Jacob et al., 2018; Parikh et al., 2018; Puma et al., 2018; Yamada & Kobayashi, 2017; Zagermann et al., 2018). **Visual fatigue is assessed in twenty-two included studies** (Abromavicius & Serackis, 2017; Abromavičius & Serackis, 2018; Bang et al., 2014; Benedetto et al., 2015; Cho & Kang, 2012; Divjak & Bischof, 2009; Iatsun et al., 2013; Iatsun et al., 2015; Jacobs et al., 2019; J. Kim et al., 2018; Julie Iskander et al., 2019; Kim, Jung, et al., 2011; Lee et al., 2010; Lin & Widyaningrum, 2018; Luo et al., 2016; Shen et al., 2019; Thai et al., 2020; T. Kim & Lee, 2020; Vienne et al., 2012; Yan Wang et al., 2019; Zhang et al., 2015; Zhou et al., 2019). **Both cognitive load and visual fatigue are assessed in one study** (Park et al., 2019).

The median number of subjects is M = 19 ± 8.89 for papers focussing on cognitive load, M = 20 ± 22.84 for papers focussing on visual fatigue, and the one paper assessing both included 50 subjects: see Figure 1.

Studies aiming at assessing cognitive load and visual fatigue with eye tracking mainly use (in descending order) Computer displays, TV, HMDs, and Projectors: see Figure 2. Only height studies used HMDs in included papers.

The studies' design is within-subjects for twenty-two of them, between-subject for eleven of them: see Figure 3.

Twenty-eight studies announce the exposure time (eight don't mention it). Exposure time to assess cognitive load is M = 30 ± 37.67 and is M = 30 ± 27.01 to assess visual fatigue. The thirty-seven studies all together have a mean exposure time of M = 36.91 minutes: see Figure 4.

The three types of stimuli mainly used in the included studies are video (twelve times), images (seven times), and texts (five times), involving low interactions (primarily viewing or clicking on a mouse): see Figure 5. Other stimuli are psychophysical tests or comparable tasks. Eleven stimuli administrations implied continuous interactions (microsurgery tasks, n-back tasks,

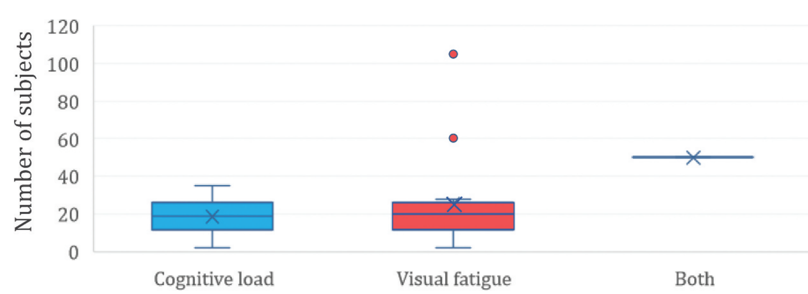

Figure 1. Number of subjects in the thirty-seven included studies.

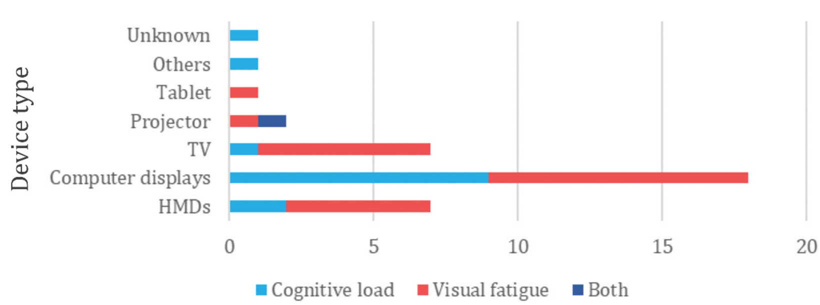

Figure 2. Devices used in the thirty-seven included studies, see Appendix B for details.

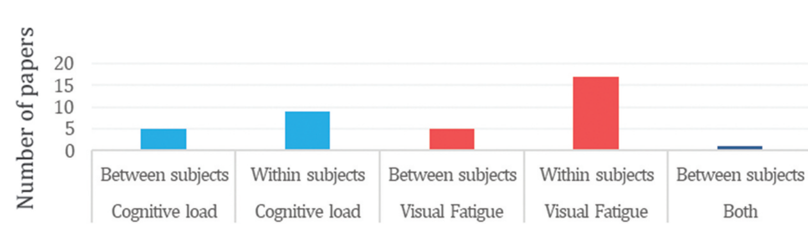

Figure 3. Study design repartition, between subjects or within-subjects.

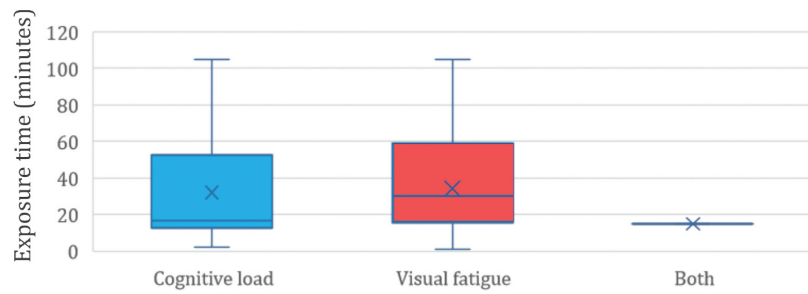

Figure 4. Exposure time to stimuli in thirty-seven included studies.

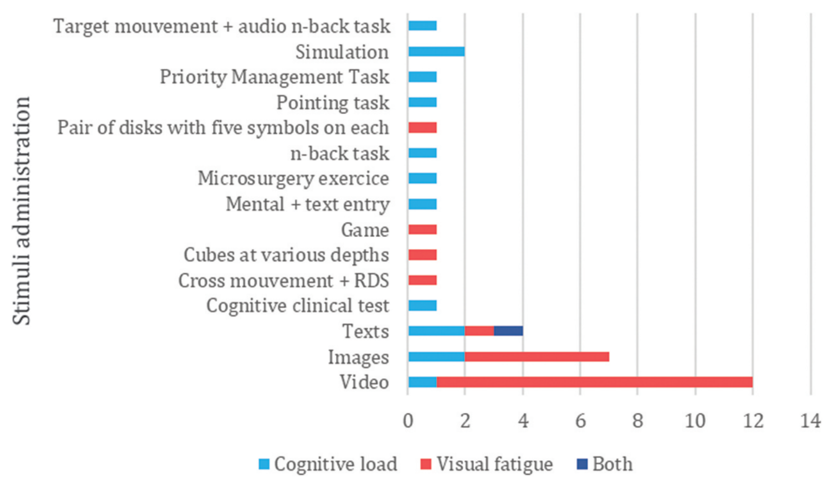

Figure 5. Stimuli administration within the thirty-seven included studies.

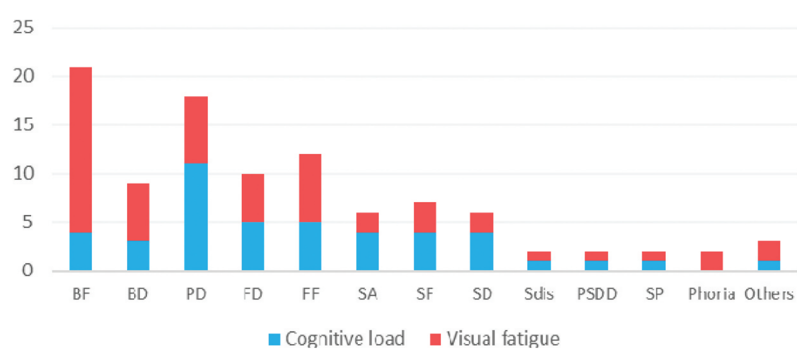

Figure 6. Features occurrence to measure cognitive load and visual fatigue based on thirty-seven included studies. BF = Blink Frequency; BD = Blink Duration; PD = Pupil diameter; FD = Fixation Duration; FF = Fixation Frequency; SA = Saccades Amplitude; SF = Saccades Frequency; SD = Saccades Duration; Sdis = Saccades disconjugacy; PSDD = Post Saccadic Disconjugate Drift; SP = Smooth pursuit. See also Appendix B.

game, and simulation). Two articles used the learning paradigm: landing simulation and microsurgery exercise (Bednarik et al., 2018; Bhavsar et al., 2018).

Figure 6 is presenting features extracted from eye tracking signals that are used in the thirty-seven included studies. Blink frequency is the most recurrent metric (seventeen times) to measure visual fatigue via eye tracking. Pupil diameter is the most recurrent metric (eleven times) to measure cognitive load via eye tracking. Those results need to be considered knowing that only height included articles are using an HMD. Learning tasks are also poorly represented by those experiments.

After identifying which features are used, we present experimental results measuring cognitive load and visual fatigue via eye tracking.

4.2. *Cognitive load measured via eye tracking: experimental results (RQ3)*

We summary fourteen experimental contributions from the 2016–2019 period using eye tracking features to assess cognitive load. The mean sampling frequency is 120 ± 277.68 Hz (three studies don't mention this information). We extracted

Table 2. Eye tracking measures of cognitive load in VR (other devices are not presented in this tab, see Appendix for complete included studies treated in the rest of this section).

Reference	Eye tracker	Indicators/Features	Device	Tasks	Main results
Bækgaard et al. (2019)	Pupil Labs	Gaze movements Pupil diameter	HTC Vive	Fitts' law task	Pupil diameter increases
Das et al. (2020)	Tobii Pro Glasses 2.0	Fixation Saccades	Oculus rift	Electric overhead traveling	Fixation frequency increases Saccades amplitude increases

studies using HMDs to reflect those devices better since it is the primary target of the present review in Table 2.

Results are consistent between each study. Overall, pupil dilation is associated with higher cognitive load and higher visual attention (Appel et al., 2018; Bednarik et al., 2018; Duchowski et al., 2018; Hopstaken et al., 2016; Kosch et al., 2018; Parikh et al., 2018; Yamada & Kobayashi, 2017; Zagermann et al., 2018). This phenomenon correlates with task duration, task difficulty, circular and sinusoidal target trajectories, and task expertise, all influencing cognitive load. Hopstaken et al. (2016) also indicate that if task motivation becomes too low, (mental) fatigue serves as an inhibitor to warn from expensive cognitive resources consumption. It allows saving cognitive resources for more rewarding activities. Due to this mechanism, fatigue decreases when motivation increases. That should be considered when the pupil diameter is recorded.

In some of the nine studies included in our review, blinks also seem to be a marker of cognitive load. Blinks duration is longer at the end of tasks (Yamada & Kobayashi, 2017) and increases depending on exposure time (Appel et al., 2018). In contradiction, Peitek et al. (2018) indicate that blinking behavior does not follow a specific pattern. Other features used in the nine studies indicate that the more fixations, the less expertise on a task (Parikh et al., 2018). This is consistent with Kosch et al. (2018), indicating an increase in eye movement during high cognitive load, and Zagermann et al. (2018) indicating a higher number of fixations and saccades associated with an increase in cognitive load.

Thus, we see consistent measures indicating pupil dilatation as a marker of cognitive load when assessed via eye tracking. A majority of studies also indicate that blinks (frequency and duration), fixations, and saccades increase because of cognitive load.

4.3. Visual fatigue measured via eye tracking: experimental results (RQ4)

We summary the twenty-two experimental contributions from the 2010–2021 period using eye tracking metrics to assess visual fatigue. The sampling frequency is M = 75 ± 162.87 Hz (three studies don't mention this information). We extracted studies using HMDs to reflect those devices better since it is the primary target of the present review in Table 3.

Some experimental results contradict visual fatigue and how it impacts the various metrics collected through eye tracking. That is the case, for instance, for blinks, which the reflex can explain compensating eye dryness. Out of nine studies evaluating blinks, height reported blinks to increase when subjects are exposed to S3D or when they approach near the end of the tasks (Lee et al., 2010; Cho & Kang, 2012; Bang et al., 2014; Iatsun et al., 2015; J. Kim et al., 2018; Kim, Choi, et al., 2011; Park et al., 2019; T. Kim & Lee, 2020). However, three studies reported blinks to decrease when subjects are exposed to S3D (Conti et al., 2017; Divjak & Bischof, 2009; Kim, Jung, et al., 2011). Two studies report saccades decreasing with S3D in relation to exposure time (Conti et al., 2017; Iatsun et al., 2015). One study indicates an increase in micro-saccades with an increased disparity in displayed images (Vienne et al., 2012). In contrast, some parameters seem to provide consistent results overstudies. For instance, pupil diameter appears to be smaller when subjects report discomfort than comfortable viewing (Abromavicius & Serackis, 2017). It is also associated with lower fixation times, which reflect increased visual fatigue.

Table 3. Eye tracking measures of visual fatigue in HMDs (other devices are not presented in this tab, see Appendix B for complete included studies treated in the rest of this section).

Reference	Eye tracker	Indicators/ Features	Device	Tasks	Main results
J. Kim et al. (2018)	Fove embedded	Blinks	Fove0	Playing game	Blinks decrease as the observation degree was strengthened beyond the typical natural state
Julie Iskander et al. (2019)	Tobii	Vergence angle	HTC Vive	Following cubes at various depths	Vergence angles significantly higher in VR than in the ideal case and higher variability as well
Jacobs et al. (2019)	Pupil Labs	Blinks Pupil diameter	HTC Vive Pro	Find and select symbols on two disks	Dynamic camera adjustment (stereoscopy parameters) lead to a higher blink rate and smaller pupil diameter than no camera changes
Shen et al. (2019)	aSee Pro VR eye tracker	Blink rate	HTC Vive	Watching videos	Blinking rate ratio (static group & constant speed group): declining (0–15 min), smooth fluctuation (15–45 min), and rising (45–50 min)
Yan Wang et al. (2019)	aGIASSDKII	Blink rate Fixation Saccades	HTC Vive	Watching video	Increasing fixation, blinking, saccades length over time (4 periods)
Thai et al. (2020)	Pupil Labs	Blink rate	HTC Vive Pro	Watching video (CGI 3D animated: 5 different)	Decreasing blink rate

We thus see that contradictory patterns when visual fatigue is assessed via eye tracking. Yet, most studies indicate that blinks increase, saccades, pupil diameter, and fixation time decrease because of visual fatigue. The following section summarizes results for cognitive load assessment.

4.4. RQ3-RQ4 summary of findings and raised issues

The review of experimental results shows that blinks increase with visual fatigue, and pupil diameter decreases with high cognitive load. However, we observe contradictory results for visual fatigue measures. Furthermore, the same variables (blinks and pupil diameter) are used to assess both visual fatigue and cognitive load. The variety of stimuli administration, eye tracking models, sampling frequency, and feature extraction strategies make it hard to generalize results and confidence in measures. Two central issues are 1) how to make sure that each feature reflects points to whether cognitive load or visual fatigue and 2) how to distinguish each state? This is critical to know in the learning context as rich virtual environments (numerous stimuli variations) are projected in HMDs. One solution relies on considering users' subjective state through the quality of experience (i.e., questionnaires). However, a deeper look at physiological strategies leading to pupil diameter and blink variations needs to be addressed to fully encompass the issue of distinguishing cognitive load from visual fatigue based on eye tracking measures.

Assessing only visual fatigue and cognitive load with eye tracking can make it hard to distinguish both states. Eye tracking measures can be interestingly be combined with Quality of experience assessment via questionnaires (Alexander et al., 2005; Egan et al., 2016; Hupont et al., 2015; Kong & Liu, 2019; Soler et al., 2017). In the VR learning context, Presence (Schroeder et al., 2017; Selzer et al., 2019; Slater, 2009), Flow (Csikzentmihalyi, 1990; Hamari & Koivisto, 2014; Kiili et al., 2014; Majaranta & Bulling, 2014; Sharek & Wiebe, 2014; Tozman et al., 2015; Wong & Csikszentmihalyi, 1991), visual discomfort or oculomotor symptoms (Zeri & Livi, 2015; H. K. Kim et al., 2018; Caldas et al., 2020; Porcino et al., 2020), and subjective cognitive load (such as the NASA-TLX) (Hart & Staveland, 1988; Matthews et al., 2020) can be considered. Ultimately, users should feel a high presence and flow when learning in VR (Lackey et al., 2016; Gabana et al., 2017; Perttula et al., 2017; Bian et al., 2018). Users should also feel low visual discomfort or oculomotor symptoms (cybersickness in general) and subjective cognitive load (Bracq et al., 2019). Users' subjective state can help to interpret eye tracking measures better. Quality of experience assessments can differ depending on individual traits (Shin, 2018) or users' familiarity with tested contents (Kim & Ko, 2019) or HMDs. The type of images, i.e., S3D or 2D, can also affect the user's quality of experience report because of visual discomfort (Guo et al., 2017, 2019; Lambooij et al., 2009; Loup-Escande et al., 2017; Selzer et al., 2019; Sohn et al., 2011; Souchet et al., 2019, 2018). Therefore, it doesn't allow to distinguish visual fatigue from cognitive load by itself, and questionnaires have limitations (Slater, 2004).

Therefore, we propose to review more fundamental contributions. Our purpose remains to distinguish visual fatigue from cognitive load when measured via eye tracking. Pilot performance and human factors measured via eye tracking use identical metrics to measure visual fatigue and cognitive load (Peißl et al., 2018). Our review also shows that the same metrics are used to assess visual fatigue and cognitive load. How can the same metrics, in identical or heterogeneous experimental paradigms, measure different psycho-physical /physiological states? Answers can be found in the brain anatomy or cognitive processing. In the following section, we review current knowledge about visual fatigue and cognitive load processing mechanisms.

5. Distinguishing visual fatigue from cognitive load (RQ5)

5.1. Autonomic nervous system-based predictions

Previous works usually relate to the arousal concept (Cohen, 2011) and specifically to the Autonomic Nervous System (ANS) to explain how psychophysiological measures reveal whether cybersickness (Dennison et al., 2016), visual fatigue (Lambooij et al., 2009), or cognitive load (Bottenheft et al., 2020; Midha et al., 2021). ANS adapts the organism to internal and external changes, maintaining bodily homeostasis and coordinating bodily responses (Johnson, 2018; Richter & Wright, 2013a).

It appears that previous works fundamentally describe cybersickness, visual fatigue, and cognitive load as stress responses (Fink, 2016) since they trigger physiological changes governed by ANS. This description is correct as ANS adapts the organism to internal and external changes, maintaining bodily homeostasis and coordinating bodily responses (Johnson, 2018; Richter & Wright, 2013a). Considering those states as stressors is conceptually sound. However, it can be confusing to rely on such a broad concept to explain the visual system's variations due to visual fatigue and cognitive load. Furthermore, relying on describing the activity of the ANS is incomplete. Being able to classify whether the activity a specific visual system behavior is induced by the sympathetic nervous system (SNS) (Richter & Wright, 2013c) or the parasympathetic nervous system (PNS) (Richter & Wright, 2013b) seems necessary. Otherwise, each state could be seen as confounding one another while performing eye tracking measures. Brain activity measures might allow to distinguishing visual system's behavior attributable to whether visual fatigue or cognitive load. However, as it has a high cost, and since learners are wearing an HMD, too many artifacts could jeopardize a precise measure (G. Kim et al., 2018). Ultimately, neural pathways of cybersickness, visual fatigue, or cognitive load are still under research. Until studies can distinguish physiological variations induced by each state, it will be hard not to rely on fundamental neurophysiological causes that are precise enough. Each state might happen to be "artifacts" noising the desired measure.

But to better reflect how cognitive load and visual fatigue might be more complex to distinguish even with brain imaging, we present their pathways in the following section to then focus on the related-visual system's behavior.

5.2. Visual fatigue and cognitive load pathways

Daniel and Kapoula report that vergence disparity processing and accommodation signals are associated with similar activities in brain regions than cognitive load: visual cortex, parietal and frontal lobes, and cerebellum (Daniel & Kapoula, 2019). In line with these findings, Terzic and Hansard (2017) indicate in a review that visual processing is linked to increased activity in parietal and occipital lobes. They also mention that fatigue is associated with a decreased activity in the visual cortex concomitantly with increased activity in the prefrontal cortex and the V3, V4, and MT areas. These areas are related to ocular control. Alongside, it appears that exposure to stereoscopic content affects the parietal and lower temporal lobe and occipital cortex (Yue et al., 2018). This effect depends on the duration of exposure. Interestingly, the neurons involved in treating significant S3D disparities are located in the parietal and lower temporal lobe areas. In contrast, the treatment of low disparities is located in the occipital cortex (Yue et al., 2018).

Therefore, cognitive load and visual fatigue induced by stereoscopic viewing are occurring in similar brain regions. This implies that such processing could lead to a similar visual system's behavior.

5.3. Processing and visual system's behavior

We found evidence that visual fatigue and cognitive load are associated with activities in similar brain regions. Visual system behavior can be associated with neurotransmitter secretion. Here we are interested in whether pupil diameter and blinks can be dissociated based on the association of the process with a specific visual system behavior.

Pupil diameter is related to cognitive activity in the same cortical regions for visual fatigue and cognitive load. This can rely on task difficulty (Eckstein et al., 2017). According to Eckstein et al. (2017), changes induced by cognitive tasks cause pupil diameter to vary by 0.5 mm. But whether task difficulty in VR is induced by learning material (intrinsic or extrinsic load) or visual stress due to vergence-accommodation conflict is hard to tell. This difficulty lies in the fact that pupil diameter is also related to *locus coeruleus* activity (involved with fear, anxiety, sleep) and Noradrenaline secretion (a neurotransmitter associated with selective attention, vigilance, and learning) (Hoffing & Seitz, 2016). Therefore, what process induces pupil diameter variation in a complex environment, such as learning tasks in VR, seems challenging to identify.

A blink can last between 100 and 500 ms. The neural networks and the brain areas involved in eye blink are still poorly identified. However, it appears to be a viable metric of central dopamine activity (Eckstein et al., 2017; Jongkees & Colzato, 2016; Rac-Lubashevsky et al., 2017) which is associated with motivation mechanisms (Wise, 2004). Blinks are also related to cognitive control, learning (attention, memory), reward, decision-making, and ultimately cognitive load (Paprocki & Lenskiy, 2017). However, blinks are also related to "dry eyes" (Rodriguez et al., 2018), which is a symptom of visual fatigue (Lambooij et al., 2009). Therefore, what process induces blinks variation in a complex environment, such as learning tasks in VR, seems also challenging to identify.

We note that cognitive load and visual fatigue activate neurotransmitters that induce similar visual system's behavior. We can't clearly distinguish cognitive load from visual fatigue. This could be due to stimuli complexity response and links between visual fatigue and cognitive load, as we present in the following section.

5.4. Possible links between visual fatigue and cognitive load

Repeated activation (Cai et al., 2017) or maintained activation (Chen et al., 2017) of stereopsis by stereoscopic images inducing sensory-motor conflicts could cause visual fatigue. In both cases, it implies that visual perception with sensory-motor conflicts induces more efforts to process those images for our brain. The task of processing images with impaired cues is difficult (Eckstein et al., 2017). It requires more cognitive resources. Therefore, visual fatigue caused by S3D is at least correlated with cognitive fatigue (Mun et al., 2012). Thus, visual fatigue and cognitive fatigue seem linked. J. Iskander et al. (2018) further state that visual fatigue is more related to mental than muscular fatigue. This would mean that visual fatigue is a reaction to cognitive overload induced by processing stereoscopic images with cues impairments. Chen and Epps (2014) are testing this perception-related cognitive load hypothesis. However, their results do not allow a generalization of a crosslink between visual fatigue and cognitive load. But in different paradigms, the cognitive load could impact the early stages of visual perceptual processing, and concurrent cognitive demands might reduce available working memory resources (Liu et al., 2018).

Park et al. (2015) indicate that links between visual fatigue and cognitive load imply that visual fatigue can be included in cognitive load theory. If we refer to Sweller (2011), extrinsic load (i.e., dependent on how information is presented and acquired) could explain the changes in visual system behavior. Sensory-motor conflicts such as vergence-accommodation conflict could be considered extrinsic loads that induce additional load on working memory (Baddeley, 2010). Then, repeated conflicts might saturate working memory resources (Bernhardt & Poltavski, 2021). Thus, visual fatigue would be a strategic response of our brain to cope with extra load induced by sensorimotor conflicts to process visual information. Abnormal or unexpected bodily signals seem to attract more processing resources (Critchley & Garfinkel, 2018).

Furthermore, cybersickness seems to impair performance like reaction time (Mittelstaedt et al., 2019). It indicates an impact of sensorimotor conflicts on cognition. This impact on performance can also be seen with vergence-accommodation conflict (Alhusuny et al., 2020). Conversely, the mental effort also seems to impact visual functions (Hynes et al., 2018; Vera et al., 2017). Therefore, the visual system shows markers of high cognitive load: increasing fixation time, increasing blinks, and decreasing pupil diameter.

5.5. RQ5 summary of findings and raised issues

Whether pupil diameter and blinks allow measuring cognitive load or visual fatigue seems unsolvable with current knowledge. Visual fatigue would arise because of cognitive overload provoked by stereoscopic images (J. Iskander et al., 2018). The exact nature of this link between cognitive load and visual fatigue remains to be determined. Available information incline to point cognitive load as inducing visual fatigue. Stereoscopic images can induce this cognitive load. Then, working memory is saturated to process such images. This overload would lead to what we know as visual fatigue as a strategy to reduce eye movements, activate more blinks to reduce dry eye (Evinger et al., 2002), and focus visual attention to process impaired cues resulting in pupil dilatation. Therefore, eye tracking features, here precisely pupil diameter and blinks, allow measuring cognitive load. Sensory cues conflict due to stereoscopic images might saturate memory resources and induce a "rest and digest" response, leading to visual fatigue.

6. Discussion and limitations

6.1. Eye tracking and Virtual Reality

Eye tracking appears to be a viable measuring tool in HMDs not restricted to visual fatigue and cognitive load (Abdulin & Komogortsev, 2015). Models are in development by research teams. Since eye tracking implementation in HMDs is relatively new, only a few contributions are using it. Using eye tracking for assessing visual fatigue (J. Iskander et al., 2018) and cognitive load (Krejtz et al., 2018; Zu et al., 2017) in VR opens to new ways to tackle human factors issues. It allows the live collection of data during the VR experience. However, several environmental variables can influence eye tracking measures, impacting data reliability (Majaranta & Bulling, 2014; Stein et al., 2021). More researches are still needed to develop stable models of data acquisition and increasing measures' reproducibility. Yet, eye tracking is an opportunity to measures the physiological response of learners while they wear HMDs. Therefore, it should be considered to collect data.

6.2. Assessing visual fatigue and cognitive load with eye tracking (RQ1-RQ2)

The purpose was to document which metrics were used to assess cognitive load and visual fatigue via eye tracking. We reviewed thirty-seven studies. Only height studies are using an HMD with eye tracking (see Appendix B). Blinks are the most recurrent feature for assessing visual fatigue, as pointed out in a systematic review by Martins and Carvalho (Martins & Carvalho, 2015). For assessing cognitive load, pupil diameter is the more recurrent feature, as pointed out in a systematic review by Charles and Nixon (2019). Most tasks and stimuli performed by humans when such measures are carried out are simpler than VR learning environments. This can be explained by the will of researchers to lower uncontrolled variables (noise factors) (Barker & Milivojevich, 2016). Yet, this lowers the relevance of the results to generalize findings to more ecological HMDs' use conditions. Although the "ecological validity" approach can be criticized (Holleman et al., 2020). Therefore, more scientific inputs are still needed to understand better the limits of assessing visual fatigue and cognitive load via eye tracking, especially while learning in VR. Eye tracking appears as a viable solution while more precise and complementary tools, such as brain imaging in HMDs (G. Kim et al., 2018), are developed.

6.3. Visual fatigue, cognitive load, and eye tracking: experimental results (RQ3-RQ4)

The purpose was to document the results when eye tracking is used to measure visual fatigue and cognitive load. We reviewed conflicting results. Most experimental studies showed blinks increase with visual fatigue. However, a few studies reported a decrease in blinks. The reasons for this discrepancy are not well understood and could be linked to the role of blinks in maintaining tear film stability to allow eyes not to be dry (Evinger et al., 2002). Blinks also vary with cognitive load.

Most experimental studies showed pupil dilation associated with higher cognitive load and higher visual attention. Pupil diameter also varies (dilation) with visual fatigue. Pupil diameter variation is a marker of cortical modulations (Peinkhofer et al., 2019).

However, our review reminds us that distinguishing whether blinks or pupil diameter variations are due to visual fatigue or cognitive load is challenging. Therefore, combining eye tracking measures to subjective experience can help to distinguish them and interpret collected data. These research issues are multidisciplinary, which motivates to use of mixed methods (Szostak, 2015).

6.4. Distinguishing visual fatigue from cognitive load

Based on our review, visual fatigue and cognitive load use the same features extracted from eye tracking to get assessed. The more recurrent features are pupil diameter and blink. We tried to distinguish measures based on more fundamental contributions through a narrative review: brain anatomy and cognitive processing. A link between visual fatigue and cognitive load is evoked or observed in several works: through covariance and location of cognitive processes (Cai et al., 2017; Chen et al., 2017; Chen & Epps, 2014; Daniel & Kapoula, 2019; Terzic & Hansard, 2017). Since VR for learning is a more complex stimuli than experiments usually assessing cognitive load and visual fatigue, this link is even more critical. Our review drives us to identify that visual fatigue can be provoked by cognitive overload induced by the process of images with sensory cues conflicts (vergence-accommodation conflict due to stereoscopy). Those impairments could induce extrinsic load (Orru & Longo, 2019; Park et al., 2015; Sweller, 2016). Therefore, eye tracking metrics are inclined to measure cognitive load while learning in VR. Distinguishing whether visual fatigue or cognitive load is measured via pupil diameter and blinks is mainly an open question. However, current contributions do point to visual fatigue that results from cognitive overload. Machine learning techniques could help select the best features from eye tracking data to assess virtual reality side effects such as visual fatigue (cybersickness) and cognitive overload (Gabana et al., 2017; Epps, 2018; Parent et al., 2019).

Previous works are usually concentrating on psycho-physical aspects of visual fatigue to explain (Fuchs, 2017) and define it (Lambooij et al., 2009). This can be explained by available assessment techniques, which were not allowing much insight into cognitive processes of visual fatigue. Therefore, the links between visual fatigue and cognitive load remained little investigated. Since little evidence is available, parsimony should be observed. These links between visual fatigue and cognitive load must be tested in different experimental conditions, and previous works reproduced with state-of-the-art techniques to challenge this hypothesis. It is critical in learning in VR since working memory saturation is a risk not to provide an efficient learning experience. Therefore, blinks are a metric of visual fatigue and pupil diameter of cognitive load. But each metric can also apply to both psycho-physiological states.

6.5. Limitations of the present review

The research questions tackled in this review are broad and the link between them sometimes hard to point based on previous literature. Terminology and paradigms can be very heterogeneous. The use of HMDs and eye tracking are not restricted to visual fatigue and cognitive load or learning. Visual fatigue and cognitive load are rarely measured while learning with HMDs. It can explain the lack of precision of the review and difficulty in linking specific review process results. To better present visual system behavior under visual fatigue or excessive cognitive load, Electrooculography or Electroencephalography could also be included in future reviews. We choose to concentrate on eye tracking in the present review as it is implemented in available HMDs. Yet, only a few articles directly using HMDs have been included. Research questions had to include works using devices other than HMDs to show which metrics were used for assessing visual fatigue and cognitive load via eye tracking. Future reviews, such as ours, might have many experimental papers based on eye tracking in HMDs since this is becoming more available. It is unclear yet to what extent the links between visual fatigue and cognitive load can impact task fulfillment and measures via eye tracking in VR.

7. Conclusion and research agenda

In this article, we proposed a review of five research questions. We link each issue to the context of learning as this is a fast-growing application of HMDs' uses (Arnaldi et al., 2018). Orru and Longo (2019) questioned and updated Cognitive load theory, widely used in research about learning. Cognitive load variations seem dependent on tasks, level of interaction required to complete the task, users' representation (avatar), and cybersickness. Positive effects of VR on cognitive load are reported in two articles, and two others are reporting negative effects. Visual fatigue occurs in VR while learning (Souchet et al., 2018) but is not impacting learning performances in virtual environments with low disparities and interactions. Visual fatigue is still an issue with HMDs (Yuan et al., 2018), especially while learning (Biggs et al., 2018) since they display stereoscopy (Matsuura, 2019), causing vergence-accommodation conflicts (Fuchs, 2017).

Eye tracking appears to be a relevant way to measure visual fatigue and cognitive load. It is implemented in HMDs by manufacturers. Therefore, it allows live data collection. Eye tracking reliability is subject to environmental conditions which require experiments to understand and categorize visual system behavior depending on contexts. We reviewed which metrics were recorded with eye tracking to measure visual fatigue and cognitive load based on thirty-seven articles. Visual fatigue is usually measured through blinks. Most experimental results indicate blinks increase as evidence of visual fatigue. Cognitive load is usually measured via pupil diameter. Most experimental results indicate dilated pupils as evidence of cognitive load, and their variations are stimuli-related. Visual fatigue and cognitive load are a function of time. Experimental paradigms rarely use complex stimuli such as learning. Blinks usually increase when subjects are exposed to S3D or near the end of tasks (in 2D and S3D). Pupil diameter is smaller when subjects report discomfort and show lower fixations. The number of saccades also decreases. Usually, high cognitive load results in pupil dilatation and longer fixation time, which is also associated with visual attention.

Distinguishing measures of visual fatigue from cognitive load obtained via eye tracking is challenging. Quality of experience (questionnaire) can help but has limitations. Recent experimental results show links between visual fatigue and cognitive load. These links between visual fatigue and cognitive load are also considered to influence eye tracking assessments.

We suggest using the mixed method for measuring visual fatigue and cognitive load and learning performances: i.e., quantitative and qualitative methods (Tashakkori et al., 2015). Peers should be working at increasing experimental studies' quality in VR (Lanier et al., 2019) by performing randomized controlled trials when possible. Using more robust metrics such as eye tracking data might help, despite the challenges inherent to this technique.

We think that future researches should focus on:

- experimental work on VR efficiency for learning purposes in different contexts and with various instruction design as well as learning purposes
- experimental work on visual fatigue impacts on learning in VR
- experimental work on VR impact on cognitive load while learning
- experimental work on of possible covariance of cognitive load and visual fatigue, especially while learning in VR
- experimental work on distinguishing cognitive load from visual fatigue when measured via eye tracking with classification techniques (machine learning)
- favoring industrialized apparatus implementing eye tracking when relevant since these are the ones that the general public will use

- formalizing theoretical and practical lessons from high-quality experimental works to allow systematic reviews and meta-analyses
- risk-benefit ratio evaluation of HMDs for learning
- updating the current review with more experimental papers using HMDs, including eye tracking in the learning context to path the way to systematic literature reviews

Virtual reality and HMDs involve risks such as visual fatigue and high cognitive load. These risks should be better measured and analyzed to allow practical use of these technologies for learning purposes. It can be done with eye tracking. The links between visual fatigue and cognitive load could influence measures performed with eye tracking. More researches on those issues are needed.

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Appendix

Appendix A. Tab of metrics to assess visual fatigue and cognitive load via eye tracking.

			Features												
			Eye-blinking			Fixation		Saccades							
Paper	Date	Purpose	Frequency	Duration	Pupil diameter	Duration	Frequency	Amplitude	Frequency	Duration	disconjugacy	Post saccadic disconjugate drift	Smooth pursuit	Phoria	Others
Appel et al.	2018	Cognitive load	1	1	1	0	0	0	0	0	0	0	0	0	0
Bednarik et al.	2018	Cognitive load	0	0	1	0	0	0	0	0	0	0	0	0	0
Bhavsar et al.	2018	Cognitive load	0	0	1	0	0	0	0	0	0	0	0	0	0
Duchowski et al.	2018	Cognitive load	0	0	1	0	0	0	0	0	0	0	0	0	0
Kosch et al.	2018	Cognitive load	0	0	0	0	0	0	0	0	0	0	1	0	0
Jacob et al.	2018	Cognitive load	1	1	1	1	1	0	1	1	0	0	0	0	0
Parikh et al.	2018	Cognitive load	0	0	1	1	1	1	0	1	0	0	0	0	0
Puma et al.	2018	Cognitive load	0	0	1	0	0	0	0	0	0	0	0	0	0
Zagermann et al.	2018	Cognitive load	1	0	1	0	1	0	1	0	0	0	0	0	0
Bækgaard et al.	2019	Cognitive load	0	0	1	0	0	0	0	0	0	0	0	0	1
Daniel and Kapoula	2019	Cognitive load	0	0	0	1	1	1	0	0	1	1	0	0	0
Das et al.	2020	Cognitive load	0	0	0	1	1	1	1	1	0	0	0	0	0
Hopstaken et al.	2016	Mental Fatigue	0	0	1	0	0	0	0	0	0	0	0	0	0
Yamada et al.	2017	Mental Fatigue	1	1	1	1	0	1	1	1	0	0	0	0	0
Divjak and Bischof	2009	Visual Fatigue	1	1	0	0	0	0	0	0	0	0	0	0	0
Lee et al.	2010	Visual Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0
Donghyun Kim et al.	2011b	Visual Fatigue	1	0	0	0	0	0	1	0	0	0	0	0	0
Cho, S.-H., & Kang, H.-B.	2012	Visual Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0
Vienne et al.	2012	Visual Fatigue	1	0	0	0	1	0	1	0	0	0	0	1	0
Iatsun et al.	2013	Visual Fatigue	1	1	1	1	1	0	0	1	1	0	0	0	0
Bang et al.	2014	Visual Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0
Benedetto et al.	2015	Visual Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0
Zhang et al.	2015	Visual Fatigue	1	1	0	0	0	0	0	0	0	0	0	0	0
Iatsun et al.	2015	Visual Fatigue	1	1	1	1	1	1	0	0	0	0	0	0	0
Luo et al.	2016	Visual Fatigue	1	0	0	0	0	0	1	1	0	1	0	0	0
Abromavicius and Serackis	2017	Visual Fatigue	0	0	1	0	1	0	0	0	0	0	0	0	0
Abromavicius and Serackis	2018	Visual Fatigue	0	0	1	0	1	0	0	0	0	0	0	1	0
Jungho Kim et al.	2018b	Visual Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0
Lin et al.	2018	Visual Fatigue	0	0	0	1	1	0	0	0	0	0	0	0	0
Zhou et al.	2018	Visual Fatigue	0	0	1	1	0	0	0	0	0	0	0	0	0
Iskander et al	2019	Visual Fatigue	0	0	0	0	0	0	0	0	0	0	0	0	1
Jacobs et al.	2019	Visual Fatigue	1	0	1	0	0	0	0	0	0	0	0	0	1
Shen et al.	2019	Visual Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0
Wang et al.	2019	Visual Fatigue	1	1	0	1	1	1	0	0	0	0	1	0	0
Thai et al	2020	Visual Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0
T. Kim & Lee	2020	Visual Fatigue	1	1	1	0	0	0	0	0	0	0	0	0	0
Park et al.	2019	Visual Fatigue and Mental Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0
		Used for Cognitive Load	**4**	**3**	**11**	**5**	**5**	**4**	**4**	**4**	**1**	**1**	**1**	**0**	**1**
		Used for Visual Fatigue	17	6	7	5	7	2	3	2	1	1	1	2	2
		Used for both Visual Fatigue and Cognitive Load	1	0	0	0	0	0	0	0	0	0	0	0	0
		Total How many Time the Metric is Used	**22**	**9**	**18**	**10**	**12**	**6**	**7**	**6**	**2**	**2**	**2**	**2**	**3**

Appendix B. Tab of experimental paradigms to assess visual fatigue and cognitive load via eye tracking.

Paper	Date	Purpose	Tested	Sample	Study Design	Display	Stimuli	Tasks	Eye-tracking	Data aquisition (Hz)	Exposure time	Method
Appel et al.	2018	Cognitive load	Task difficulty and time	28	Between subjects	[Computer display] 22″	n-back task	Pressing bouton if previous letter is displayed	SMI	250	12 minutes 83 secondes	Detecting n letters, pressing one or two buttons
Bednarik et al.	2018	Cognitive load	Novice *vs* Experts	11	Between subjects	Microscope	Microsurgery exercice	penetration, needle handling and knotting	Intensity BlackMagic	30	?	Task completion, Questionnaires
Bhavsar et al.	2018	Cognitive load	Difficulty	2	Within subjects	?	Simulation	Landing procedure	Tobii TX300	120	?	Task complettion x5
Duchowski et al.	2018	Cognitive load	Calcul accuracy and Cognitive load	13	Between subjects	[Computer display]	Mental + text entry	Counting and entering count	EyeLink 1000	?	?	Tasks and Questionnaire
Kosch et al.	2018	Cognitive load	Speed and task difficulty	20	Between subjects	[Computer display] 22″	Target mouvement + audio n-back task	Following target and pressing bouton if letter displayed	SMI RED	250	12 minutes 30 secondes	Following target while completing n-back, Questionnaires
Jacob et al.	2018	Cognitive load	Comprehension	13	Within subjects	[Computer display]	Texts	Reading, Text Comprehension	SMI REDn Scientific	60	?	Reading
Parikh et al.	2018	Cognitive load	Accuracy based on cognitive load	10	Within subjects	[Computer display]	Texts	Word comprehension	Tobii X2	60	?	Training, Reading, Word Comprehension test
Puma et al.	2018	Cognitive load	Difficulty	20	Within subjects	[Computer display] DELL 19″, 75 Hz, 1024 ×768 pixels	Priority Management Task	Gauge monitoring, tracking task, letter detection. small calculation problems	EyeLink 100	1000	60 minutes	Task completion, Questionnaires
Zagermann et al.	2018	Cognitive load	Visual perception task accuracy and Cognitive Load	26	Between subjects	[Computer display] Microsoft Perceptive Pixel 550	Images	Visual perception tasks (color, shape and color + shape)	SMI	120	?	Tasks and Questionnaire
Bækgaard et al.	2019	Cognitive load	Mouse, head-position, foot-mouse, and gaze-pointing	27	Within subjects	HTC Vive	Pointing task	Fitts' law task	Pupil Labs	120	30 minutes	Task completion, Questionnaires
Daniel and Kapoula	2019	Cognitive load	Control condition *vs* Prism condition (usual correction + 8Δ base-out) *vs* Lens condition (usual correction + −2.50D)	24	Within subjects	[Computer display]	Cognitive clinical test	Completing Stroop test	EyeSeeCam VOG	?	2.25 minutes	Reading, denomination and interference, 1 minute rest after each condition closing eyes
Das et al.	2020	Cognitive load	Hazards sources, Activity complexity level, trial sequences	12	Within subjects	Oculus rift	Simulation	Electric overhead traveling crane operations	Tobii Pro Glasses 2.0	?	18 minutes	Task completion, Questionnaires
Hopstaken et al.	2016	Mental Fatigue	With *vs* Without distrators	35	Within subjects	[Computer display]	Images	Decision targeted letter or not in faces images by responding with the corresponding letter on a keyboard	SMI RED250	60	1 hour 45 minutes	Task training, 1 task + Questionnaire x 3, Reward
Yamada et al.	2017	Mental Fatigue	Paced Auditory Serial Attention Test after Watching video	18	Within subjects	[TV]	Video	Watching, Completing mPASAT	infrared EMR ACTUS	60	15 minutes	Questionnaire, Watching Video, Attention Test x 2, Questionnaire Watching video
Divjak and Bischof	2009	Visual Fatigue	read *vs* work	6	Between subjects	[Computer display]	Video	Watching videos	Web-camera	?	?	?

(*Continued*)

Appendix B. (Continued).

Paper	Date	Purpose	Tested	Sample	Study Design	Display	Stimuli	Tasks	Eye-tracking	Data aquisition (Hz)	Exposure time	Method
Lee et al.	2010	Visual Fatigue	S3D *vs* 2D + viewing distance	24	Between subjects	[Computer display] LCD 21″	Video	Watching movie	Web-camera	15	29.5 minutes	Questionnaire, movie for about 30 minutes and questionnaire
Donghyun Kim et al.	2011b	Visual Fatigue	S3D+disparity *vs* S3D *vs* 2D	2	Within subjects	[Computer display] 55″ stereoscopic display	Video	Watching videos	[camera] Sony DCR-SR45, night mode	?	20 minutes	watching each movie per day
Cho, S.-H., & Kang, H.-B.	2012	Visual Fatigue	disparities / time / display size	20	Between subjects	[TV] LG 3D Cinema TV 55″ and 27″	Video	Watching movie	SceneCamera, Arrington Research	?	3, 10 or 15 minutes	Questionnaire, viewing, Questionnaire
Vienne et al.	2012	Visual Fatigue	watching (±90 *vs* ±45 *vs* 0 arcminutes) and 3D angle estimation	9	Within subjects	[Computer display]	Cross mouvement + RDS	Fixating a cross	Eyelink 1000	?	?	Repeating 270 times tasks (varying disparities), during 3 sessions, questionnaire (SSQ)
Iatsun et al.	2013	Visual Fatigue	S3D	10	Within subjects	[TV] Hyundai TriDef S465D	Video	Watching movie sequences	Tobii TX-120	120	1 hour	10 minutes x 6 (movies)
Bang et al.	2014	Visual Fatigue	S3D before *vs* after	15	Within subjects	[TV] 60″	Video	Watching movie	high-speed camera of 4 mega pixels	60	30 minutes	pre- and post-watching S3D video measurements for 1 minute + Questionnaire
Benedetto et al.	2015	Visual Fatigue	Spritz *vs* regular screen	60	Between subjects	[Computer display] LCD 22″ Dell P2210 + [Spritz]	Texts	Reading	SMI RED 5	500	25 minutes	Reading then Questionnaire
Zhang et al.	2015	Visual Fatigue	Polarized *vs* Curvate display	60	Between subjects	[TV] LCD 40″ L409HBD FHD	Video	Watching videos	Gaze Intelligence	?	1 hour 45 minutes	Watching 5 minutes video then 110 minutes video, Questionnaire
Iatsun et al.	2015	Visual Fatigue	S3D *vs* 2D	20	Within subjects	[TV] Hyundai TriDef S465D	Video	Watching movie sequences	Tobii TX-120	120	1 hour	10 minutes x 6 (movies), SQQ between each viewing
Luo et al.	2016	Visual Fatigue	Flat *vs* curved display	27	Within subjects	[Computer display] Samsung 34″ curved monitor (S34E790C) and Samsung 34″ flat monitor″	Images	Finding the zebras with mouse	EyeLink II	500	55 minutes	Questionnaire, Clinical tests for binocular statuts, tasks, eye-tracking, Questionnaire, Cinical tests
Abromavicius and Serackis	2017	Visual Fatigue	S3D and comfort	12	Within subjects	[Computer display]	images (anaglyphe)	Achieve depth perception	tobii T120	60	40 minutes	120 stereo images, 5 secondes rest after each image, 30 secondes rest after 40 and 80 images
Abromavicius and Serackis	2018	Visual Fatigue	S3D and comfort	28	Within subjects	[Computer display] 17″ stereoscopic display	images (anaglyphe)	Achieve depth perception	tobii T120	60	40 minutes	120 stereo images, 5 secondes rest after each image, 30 secondes rest after 40 and 80 images

(*Continued*)

Appendix B. (Continued).

Paper	Date	Purpose	Tested	Sample	Study Design	Display	Stimuli	Tasks	Eye-tracking	Data aquisition (Hz)	Exposure time	Method
Jungho Kim et al.	2018b	Visual Fatigue	Natural *vs* Monitor *vs* HMD	21	Within subjects	[Computer display] 24″ Ultron 2457 Ultra monitor / [HMD] FOVE0	Game	Playing game	FOVE0	?	1 minute	No particular stimuli, game
Lin et al.	2018	Visual Fatigue	Paralaxes at the screen *vs* 20 cm *vs* 50 cm negative	10	Within subjects	[Projector screen] 3D ViewSonic (PJD6251)	Cubes and Balls	Clicking on the object	Tobii X2	60	> 1 hour	Tasks and Rest
Zhou et al.	2018	Visual Fatigue	Watching images with different disparities	24	Within subjects	[TV] 47″ polarized HD 3D display (LG 47LA6600)	Images	Watching	Tobii X120	?	110 seconds	Watching images for 10 seconds, Questionnaire
Iskander et al	2019	Visual Fatigue	4 different depths	26	Within subjects	HTC Vive	Cubes at various depths	Fiwate and follow cube: 1.5 m, 1.75 m, 2 m, 3 m, and 4 m	Tobii	120	3 minutes	Task completion
Jacobs et al.	2019	Visual Fatigue	Dynamic camera adjustment	18	Within subjects	HTC Vive Pro	Pair of disks with five symbols on each	Find and select symbols on two disks	Pupil Labs	120	20 minutes	Task completion + Questionnaire
Shen et al.	2019	Visual Fatigue	Disparity changes, static group, constant speed group and non-constant speedgroup	17	Within subjects	HTC Vive	Video	Watching movie	aSee Pro VR	?	60 minutes	Task completion + Questionnaire
Wang et al.	2019	Visual Fatigue	Relax *vs* fatigue	105	Within subjects	HTC Vive	Video	Watching videos	aGIASSDKII	75	3 minutes	Task completion + Questionnaires
Thai et al	2020	Visual Fatigue	Diffrent active breaks to reduce visual fatigue: hand in a thumb-up pose	20	Within subjects	HTC Vive Pro	Video	Watching videos	Pupil Labs	?	30 minutes	Task completion + Questionnaires
T. Kim & Lee	2020	Visual Fatigue	Gamma, color temperature, birtghtness changes	20	Within subjects	[Tablet]	Images (video)	Watching images	Infrared cameras	30	16 minutes	Task completion
Park et al.	2019	Visual Fatigue and Mental Fatigue	Different display curvatures	50	Between subject	[Projector screen] 27″	Texts	Correcting texts	Acton (USA) Eye-tracker	?	15 minutes	Questionnaire, Proofreading tasks, Questionnaires