Immersive media experience: a survey of existing methods and tools for human influential factors assessment

Marc-Antoine Moinnereau1 · Alcyr Alves de Oliveira Jr2 · Tiago H. Falk1

Received: 23 November 2021
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2022

Abstract
Virtual reality (VR) applications, especially those where the user is untethered to a computer, are becoming more prevalent as new hardware is developed, computational power and artificial intelligence algorithms are available, and wireless communication networks are becoming more reliable, fast, and providing higher reliability. In fact, recent projections show that by 2022 the number of VR users will double, suggesting the sector was not negatively affected by the worldwide COVID-19 pandemic. The success of any immersive communication system is heavily dependent on the user experience it delivers, thus now more than ever has it become crucial to develop reliable models of immersive media experience (IMEx). In this paper, we survey the literature for existing methods and tools to assess human influential factors (HIFs) related to IMEx. In particular, subjective, behavioural, and psycho-physiological methods are covered. We describe tools available to monitor these HIFs, including the user’s sense of presence and immersion, cybersickness, and mental/affective states, as well as their role in overall experience. Special focus is placed on psycho-physiological methods, as it was found that such in-depth evaluation was lacking from the existing literature. We conclude by touching on emerging applications involving multiple-sensorial immersive media and provide suggestions for future research directions to fill existing gaps. It is hoped that this survey will be useful for researchers interested in building new immersive (adaptive) applications that maximize user experience.

Keywords Immersive media experience · Quality of experience · Virtual reality · Cybersickness · Mulsemedia

Introduction
It is predicted that the global augmented/virtual reality (AR/VR) market will reach US$814.7 billion by 2025 [1] through steady and continuous growth of new mobile applications and the appearance of the fifth-generation (5G) wireless networks worldwide. 5G networks promise faster speeds, lower latency, wider coverage, and more stable connections. Applications across multiple verticals are projected, including entertainment and media, gaming, healthcare, automobile, aerospace and defense, manufacturing, retail, and education, to name a few. In fact, as recently emphasized by Qualcomm, 5G coupled with VR will be essential for the development of next-generation immersive experiences and will enable applications, such as six degrees of freedom immersive content, automotive video streaming, crowded event sharing, remote control, and the tactile internet. Recent projections show that the number of users, in the United States alone, will double by 2022 [2]. To fully unlock this potential, however, the effectiveness of these emerging applications will not only depend on their technical capabilities, but also on the quality of experience (QoE) they provide to the user [3].

More generally, QoE refers to the “degree of delight or annoyance of applications or services resulting from the fulfillment of his or her expectations with respect to the utility and/or enjoyment of the application or service in the light of the users personality and current state” [4]. When it comes to immersive media and content, immersive media experiences (IMEx) [5] build on the QoE concept by also including factors such as sense of presence and immersion, as well as motion sickness (cybersickness), to name a few. In fact, QoE and IMEx are driven by three influential factors (IFs): system, context, and the (human) user.

Within immersive experiences, devices play a large role as system influential factors [5], as the capability of
accurately tracking the user’s behaviors (e.g., body/head position, movements, eye tracking) can affect the interaction, as well as the sense of presence and immersion [6]. Device design in terms of portability, usability, field-of-view, visual quality, and ergonomic aspects have been shown to also impact the user experience [7, 8]. Moreover, multisensory experiences involving audiovisual media with e.g., haptic, olfactory, and gustatory stimuli in VR can also drastically affect the overall IMEx [9]. As highlighted in [5], in turn, contextual IFs describe the user’s environment, such as physical, temporal, social, economic, task, and technical characteristics. Sometimes it is difficult to separate system and context completely and they are evaluated together. On the other hand, human influential factors include “any variant or invariant property or characteristic of a human user,” i.e., factors related to emotional state, expectations, attention, among others [4]. As highlighted in [5], “the fact that not every human becomes equally immersed in the same book, movie, or game, illustrates that human IFs are of very high relevance for an IMEx.” Moreover, the sensitivity of each user towards incongruency and timing differences between perceptual modalities can lead to discomfort, visual fatigue, and motion sickness (also known as cybersickness), which has been reported to affect between 30 and 80% of users, with symptoms potentially lasting for several hours post VR exposure.

In order to continuously improve VR technology, constant evaluation is needed to measure IMEx, taking all three IFs into account. While system and context have been widely explored, the impact of human influential factors on IMEx is a less studied topic, thus will be the focus of this present paper. In particular, two assessment methods have been commonly used for this purpose, namely: subjective and instrumental. The latter can be further classified as behavioural and psycho-physiological. Conventionally, subjective methods consist of questionnaires, administered after the VR experience, that measure certain aspects of the human experience itself [10–14]. As can be expected, subjective tests can be biased, lack temporal resolution, and allow only for offline analysis, thus cannot be used to improve the IMEx in real-time. On the other hand, (instrumental) behavioural IFs assessment is based on tracking user behaviours, such as facial expression, body gestures, and social interaction. These behaviours can be generated and controlled in a non-intentional, automatic manner and do not necessitate conscious introspection as in subjective methods.

Over the last few years, developments in biosensors [15] have allowed for numerous IFs to be monitored in real-time in immersive environments [16]. As such, (instrumental) psycho-physiological methods have emerged and aim to find correlates between perceptual QoE/IMEx features and physiological metrics [17]. Physiological signals have been used, for instance, to measure stress [18], engagement [19], emotions [20], sense of presence [21], immersion [22], and overall experience [23, 24], thus can play a key role in advancing VR applications. Some physiological signals that have shown useful for experience assessment include the electroencephalogram (EEG), electrocardiogram (ECG) and measured heart rate (HR) or heart rate variability (HRV), electrooculogram (EOG) and eye blinks, electrodermal activity (EDA) [25, 26], and cerebral blood-flow measured via near-infrared spectroscopy (NIRS) [27]. Moreover, recent advances in dry/wireless electrodes [28, 29] and motion artifact suppression [30] have allowed for biosensors to be integrated directly into VR headsets (e.g., [31]) and to monitor human IFs in real-time [32], as shown in Fig. 1.
the obtained signals. Unlike conventional video QoE assessment where users are sitting and static [4], VR experiments have users moving around and exploring the virtual environment, hence hampering signal quality and overall human IF measurement. Ultimately, monitoring of human biosignals while immersed in virtual reality will allow us to characterize factors such as cybersickness, perception of immersion, and overall experience, thus allowing for experiences to be adapted in real-time to maximize the IMEx. As VR becomes more popular, assessment of IMEx has become critical in order to develop applications that can be used and enjoyed by the masses.

This paper presents a survey of the literature on IMEx assessment, in particular on HIFs assessment, to find out what the latest trends and innovations are. We start by looking at existing subjective methods focusing on the user’s sense of presence, perception of immersion, cybersickness, emotional state, and experience. Next, we focus on behavioural and psycho-physiological measures, describing the latest biosensors and tools used. While the focus of this survey will be on psycho-physiological assessment, we provide a brief summary of the other methods and guide the reader to available review papers on the topics. Lastly, we venture into next-generation applications encompassing multiple senses, beyond audio-visual, to improve realism and immersion. We conclude with a brief discussion on limitations and provide the reader with recommendations for future studies.

**Subjective IMEx assessment**

Subjective evaluations are the most common method for IMEx/HIFs assessment. They are usually applied shortly after the end of an experiment through questionnaires or rating scales. Their composition can vary according to the purposes of a specific experiment or application, or could be more generic and applicable across several contexts. Moreover, due to the lack of a common understanding and definition of the terms presence and immersion, a plenitude of different questionnaires have been developed. Recently, questionnaires that have proven their effectiveness via pen-and-paper assessments have also been integrated into virtual reality [33–35], hence reducing study duration and discomfort to the users [36]. Here, we focus on four aspects of IMEx measured from subjective assessments, including: sense of presence and perception of immersion, user quality of experience, cybersickness, and mental/affective state.

**Questionnaires for presence assessment**

Presence within the context of virtual reality is defined as one’s sense of being in the virtual world. One of the fundamental aspects of VR is the ability to create and maximize the sense of presence of the user [12, 37, 38], hence making them feel like they are present in the virtual world. While sense of presence and immersion are closely related, numerous studies have categorized presence [39] based on what is being measured [11, 12, 40–43]. For example, [44] lists three types of presence in VR, namely personal presence (also called self-presence), i.e., the feeling of “being there,” social presence (also called co-presence), i.e., the sense of “being there with others,” and environmental presence (also called physical, telepresence or spatial presence), where participants feel immersed physically in the virtual environment and interact with virtual objects.

In other words, the sense of presence is influenced by a range of elements including equipment factors (as physical barriers and device awareness), user’s subjective factors (personality traits or immersion propensity), social factors (interactions with VR characters), and affective [45], such as the emotions about self (anxiety, paranoid ideation, detachment), emotions about others (loneliness, retrospective emotions, recognition of self), thoughts about self (memories, social judgement), thoughts about others (paranoid ideation, narrative), physiological reactions (anxiety, cybersickness), behaviour of avatars (narrative, duration of interaction, characteristics), interactivity with environment (movement, familiarity), and environmental characteristics (restrictions) [46].

Here, we present the most common questionnaires that have been created to measure sense of presence in VR. Table 1 lists the questionnaires, how many subjects they were validated on, subscales used, rating scale, number of items rated, as well as which media they are applicable to, namely: virtual environment (VE), cross-media (CM), shared virtual environment (SVE), and 2D screens. Moreover, citation numbers were taken from Google scholar and latest numbers were confirmed at the date of paper submission. As can be seen, most of the questionnaires were created more than 20 years ago. The most popular and most widely used to date is the so-called Presence Questionnaire (PQ) [12] that has been cited over 5250 times and measures involvement, sensory fidelity, adaptation/immersion, and the interface quality. The GlobalED Questionnaire [47] is the most popular for social presence, with over 2500 citations, and the Igroup Presence Questionnaire [40] for spatial presence, involvement, and the experienced realism. Although PQ continues to be the standard in virtual reality research, it has been argued that the instrument does not provide a measure of presence, but of the individual’s responses to various aspects of the virtual reality system, through a series of questions that involve the expression of the respondent’s opinion about the evaluated factors (i.e., control, sensory, distraction, and realism factors) [41]. The interested reader is referred to [48–50] for a complete in-depth review on subjective presence questionnaires.
Table 1: List of commonly used presence questionnaires for subjective IMEx assessment

| References | Questionnaires | Subject | Subscale | Rating scale | Citations | Items | Media |
|------------|----------------|---------|----------|--------------|-----------|-------|-------|
| [54]       | Barfield et al. Questionnaire 1 | 86      | Personal presence | 0–100       | 329       | 2     | VE    |
| [55]       | Barfield et al. Questionnaire 2 | 12      | Monoscopic vs stereoscopic display, head-tracking, field-of-view | 5-point     | 409       | 3     | VE    |
| [56]       | Memory characteristic Questionnaire (MCQ) | 90      | Presence, Judgment, Attention, Coherence, and Field-of-view | 7-point     | 1257      | 21    | SVE   |
| [43]       | Slater-Usoh-Steed Questionnaire (SUS) | 24      | Presence from internal/external factors | 7-point     | 908       | 6     | VE    |
| [57]       | Lombard & Ditton Questionnaire | 600     | Social presence, Realism, Transportation, and Immersion | Not defined | 332       | 103   | CM    |
| [47]       | GlobalED Questionnaire | 50      | Social presence | 5-point     | 2560      | 14    | SVE   |
| [58]       | Kim & Biocca Questionnaire | 96      | Physical, Virtual or imaginary presence | 8-point     | 860       | 8     | 2D screen |
| [59]       | Reality Judgment and Presence Questionnaire (RJPQ) | 124     | Reality judgment, and Attention | 10-point    | 225       | 18    | VE    |
| [12]       | Presence Questionnaire (PQ) | 152     | Presence, Involvement, and Immersion | 7-point     | 5254      | 32    | VE    |
| [60]       | Thie & Van Wijk Questionnaire | 48      | Social presence | Not defined | 38        | Not defined | VE    |
| [61]       | Presence & Realism | Not defined | Virtual art exhibits | 4-point     | 8         | 10    | VE    |
| [62]       | Dinh et al. Questionnaire | 322     | Visual, Olfactory, Auditory, and Tactile | 0–100       | 537       | 14    | VE    |
| [63]       | Murray et al. Questionnaire | 10      | Impact of the sound on the sense of presence | 5-point     | 56        | 5     | VE    |
| [64]       | Nichols et al. Questionnaire | 24      | Influence of the headset, and Auditory stimuli | 7-point     | 231       | 9     | VE    |
| [65]       | Basdogan et al. Questionnaire | 10      | Social presence | 7-point     | 497       | 8     | SVE   |
| [66]       | ITC - Sense of Presence Inventory (ITC-SOPI) | 604     | Sense of Physical space, Engagement, Ecological validity, and Negative effects | Not defined | 1121      | 44    | CM    |
| [67]       | IPO Social Presence Questionnaire (IPO-SPQ) | 34      | Social presence | 7-point     | 151       | 17    | 2S screen |
| [68]       | Gerhard et al. Questionnaire | 27      | Immersion, Communication, Involvement, Awareness, Nature of the environment, and User interface | 7-point     | 82        | 19    | SVE   |
| [69]       | Krauss et al. Questionnaire | 165     | Presence | Rating scale | 14        | 42    | VE    |
| [40]       | Igroup Presence Questionnaire (IPQ) | 246     | Spatial Presence, Involvement, and Realism | 5-point     | 1283      | 14    | SVE   |
| [70]       | Swedish Viewer-User Presence Questionnaire (SVUP) | 32      | Enjoyment, Sound quality, Presence, and Cybersickness | 5-point     | 72        | 19    | VE    |
| [71]       | Schroder et al. Questionnaire | 132     | Physical and Social presence | 5-point     | 177       | 11    | SVE   |
| [72]       | Bailenson et al. Questionnaire | 50      | Social presence | 7-point     | 493       | 5     | VE    |
| [73]       | CMC Questionnaire/Social presence and Privacy Questionnaire (SPPQ) | 310     | Social presence | 5-point     | 592       | 17    | CM    |
| [74]       | Networked Minds | 76      | Co-presence, Psychological Involvement, and Behavioral Engagement | 7-point     | 405       | 40/38 | SVE   |
| [75]       | E2I Questionnaire | 10      | Presence, and Enjoyment | 7-point     | 451       | 14    | VE    |
| [76]       | Nowak & Biocca Questionnaire | 134     | Telepresence, Copresence, and Social presence | 7-point     | 833       | 29    | SVE   |
| [77]       | Cho et al. Questionnaire | 32      | Visual realism, and Presence | 0–100       | 40        | 4     | VE    |
| [78]       | MEC-SPQ | Not defined | Spatial presence, and Attention | 5-Point     | 206       | 8     | VE    |
Questionnaires for user experience assessment

User experience is defined as perceptions and responses resulting from the use of a system. It is assessed by various measures of involvement such as engagement, flow, immersion, and encapsulates the user’s preferences and behaviour during use. Immersion represents the instrumental level of sensory fidelity provided by a VR system, and in applications requiring a certain level of suspension of disbelief, it plays a crucial role in overall experience. Immersion also modulates user engagement and can result in achieving a flow state. In VR, sensory immersion is defined as “the degree in which the range of sensory channels are engaged by the virtual simulation” [51]. Moreover, flow experience is often considered as an important standard of ideal user experience and keeping users in the flow state is considered as one important goal in VR system design [52]. Here, we list the most commonly used user experience questionnaires in Table 2, alongside how many subjects they were validated on, the subscales used, rating scale, number of items rated, as well as which media they are applicable to, i.e., VE, SVE, CM, or 2D screens. The interested reader is referred to [53] for a complete in-depth review on subjective user experience questionnaires.

Questionnaires for cybersickness assessment

Cybersickness is one of the main limitations of VR as it induces physiological changes that affect the users’ sympathetic and parasympathetic activities. Reports suggest that cybersickness can affect between 30 and 80% of users and that symptoms can last for several hours [98]. The most common hypothesis to explain cybersickness is the sensory conflict theory. Indeed, cybersickness is the result of conflicts between three sensory systems: visual, vestibular and proprioceptive. Cybersickness is a complex phenomenon and, although motion cues play a primary role, multiple factors are known to contribute to the occurrence of sickness. These include factors related to the characteristics of the stimuli (e.g., spatial frequency, reactivity of the system, wideness of the field-of-view) and factors related to predispositions of the user (e.g., gender, age, predisposition to migraines) [99]. The most evident symptom of cybersickness is nausea, but there are also others, including general discomfort, headache, disorientation, and eye strain. Symptom intensity and duration are quite variable and depend on the characteristic of the stimulus, as well as user predisposition to cybersickness. In the majority of cases, the symptoms disappear a few minutes after the end of the stimulation. In particular cases, the symptoms could still be present 6 hours after the VR experience [100]. There have been a number of questionnaires developed to evaluate cybersickness, as shown in Table 3. Although the Simulator Sickness Questionnaire (SSQ) is widely used in VR research, it was originally developed to measure motion sickness in simulators [101]. It has been criticized for its psychometric qualities and applicability in VR as a measure of cybersickness [102]. Recent questionnaires have since been developed specifically for HMDs, such as the Virtual Reality Symptom Questionnaire (VRSQ) [103], and have shown better indicators of validity [104]. Moreover, there are questionnaires that also focus on the severity [105] of cybersickness.

| References | Questionnaires       | Subject | Subscale                                                                 | Rating scale | Citations | Items | Media |
|------------|----------------------|---------|--------------------------------------------------------------------------|--------------|-----------|-------|-------|
| [79]       | Temple Presence Inventory | 46      | Spatial presence, Social presence-actor, Passive social presence, Active social presence, Presence as engagement, Presence as social richness, Presence as social realism, and Presence as perceptual realism | 7-point      | 223       | 42    | CM    |
| [80]       | Tendency Toward Presence Inventory | 499   | Cognitive Involvement (active and passive), Spatial Orientation, Introversion, Ability to Construct Mental Models, and Empathy | 5-point      | 57        | 41    | VE    |
| [81]       | The German VR Simulation Realism Scale | 151   | Visual Realism, Audience Behavior and Appearance, and Sound Realism | 5-point      | 18        | 14    | VE    |
| [82]       | Multimodal Presence Scale (MPS) | 161/118 | Physical, Social, and Self presence | 5-point      | 62        | 38/15 | VE    |
| [83]       | Short QoE questionnaire | 36      | Perceptual quality, Presence, Acceptability, and Cybersickness           | 5-point      | 84        | 5     | VE    |
The questionnaires have been regarded as being too long, so shorter versions have also been explored and validated, such as the MSSQ-Short [106], and the Simplified SSQ [107]. The interested reader is referred to [102, 108, 109] for an in-depth review on cybersickness assessment in VR.

**Questionnaires for affective/mental state monitoring**

The word “experience” in the user experience expression implies that there is emotional involvement when users explore immersive media content. For example, users may feel happy, satisfied, frustrated, overjoyed, or disappointed by the experience. In general, emotional experiences can be described by three emotion primitives: valence (the pleasantness of a stimulus), arousal (the intensity of emotion provoked by a stimulus), and dominance (the degree of control exerted by a stimulus). The Self-Assessment Manikins is a picture-based questionnaire widely used to assess valence, arousal, and dominance [114]. Graphical tools allow users to report their feelings efficiently and intuitively by indicating or rating the part of the figure that best represents their current affective state. Graphical self-report instruments are appealing for the measurement of affective experiences since

| References | Questionnaires | Subject | Subscale | Rating scale | Citations | Items | Media |
|------------|----------------|---------|----------|--------------|-----------|-------|-------|
| [84]       | Immersive Experience Questionnaire (IEQ) | 244     | Cognitive, Involvement, Emotional involvement, World dissociation, and Challenge | 5-point | 1791     | 31    | CM    |
| [85]       | GameFlow Questionnaire | Not defined | Concentration, Player Skills, Control, Challenge, Feedback, Clear goals, Immersion, and Social Interaction | GameFlow criteria | 2715 | 35 | CM |
| [86]       | EGameFlow Questionnaire | Not defined | Concentration, Control, Knowledge Management, Challenge, Goal clarity, Immersion, Feedback, and Social Interaction | 0–100 | 786 | 42 | CM |
| [87]       | Game Engagement Questionnaire (GengQ) | 153     | Immersion, Flow, Presence and Absorption | 5-point | 982 | 19 | CM |
| [88]       | Game Experience Questionnaire (GexpQ) | Not defined | Immersion, Competence, Flow, Negative effect, Positive effect, and Challenge | 5-point | 396 | 33 | CM |
| [89]       | EVE-GP questionnaire | 2182     | Multidimensional UX in video games | 7-point | 33 | 180 | CM |
| [90]       | Narrative game questionnaire | 340     | Curiosity, Concentration, Control, Challenge, Comprehension, and Empathy | 7-point | 266 | 27 | CM |
| [91]       | SCI Model Questionnaire 10 | 234     | Sensory immersion, Challenge-based immersion, Imaginative immersion | 5-point | 1395 | 18 | CM |
| [92]       | Core Elements of the Gaming Experience (CEGE) questionnaire | 15 | Enjoyment, Frustration, Control, Puppetry, Facilitators, Ownership, Game-play, and Environment | 7-point | 252 | 38 | CM |
| [93]       | Unified questionnaire on User eXperience in Immersive Virtual Environment | 116 | Presence, Engagement, Immersion, Flow, Usability, Skill, Emotion, Experience consequence, Judgement, and Technology adoption | 10-point | 76 | 87 | VE |
| [94]       | Presence-Flow-Framework (PFF) | 68 | Perceptual experience, Situational involvement, and Competence | 7-point | 165 | 124 | VE |
| [95]       | Presence-Involvement-Flow Framework2 (PIFF2) | 91 | Presence, Involvement, and Flow | 7-point | 79 | 139 | VE |
| [96]       | Virtual Reality Neuroscience Questionnaire (VRNQ) | 40 | QoE, Game mechanics, and In-game assistance | 7-point | 29 | 20 | VE |
| [97]       | User Experience Questionnaire (UEQ) | 144 | Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty | 7-point | 1297 | 26 | CM |
they do not require the users to verbalize their emotions. Instead, they rely on the human ability to intuitively and reliably attribute emotional meaning to (simple) graphical elements. However, the user may not be able to easily interpret the pictorials and therefore may have difficulty identifying with them [115]. More recently, a variant was proposed based on emojis (e.g., smiling or frowning faces). Emojis are pictographs or ideograms representing emotions, concepts, and ideas. Emoji-based rating tools are increasingly becoming popular tools as self-report instruments to measure user and consumer experience. The EmojiGrid, for example, has been proposed as a self-report tool for the assessment of VR-evoked emotions [116]. The interested reader is referred to [117–119] for more details on user emotional/affective state assessment in VR.

**Table 3** List of commonly used cybersickness questionnaires for subjective IMEx assessment

| Reference | Questionnaires                        | Subject | Subscale                          | Rating scale | Citations | Items | Media |
|-----------|--------------------------------------|---------|-----------------------------------|--------------|-----------|-------|-------|
| [101]     | Simulator Sickness Questionnaire (SSQ)| Not defined | Nausea, Oculomotor, and Disorientation | 4-point      | 4206      | 16    | CM    |
| [110]     | Motion Sickness Assessment Questionnaire (MASQ) | 310 | Motion-sickness | 9-point      | 297       | 16    | CM    |
| [106]     | Motion Sickness Susceptibility Questionnaire-Short (MSSQ-Short) | 257 | Motion-sickness | 4-point      | 273       | 18    | VE    |
| [105]     | Fast Motion Sickness Scale (FMS)       | 126 | Motion-sickness | 0–20         | 277       | 1    | VE    |
| [103]     | Virtual Reality Sickness Questionnaire (VRSQ) | 24 | Oculomotor, and Disorientation | 4-point      | 212       | 9    | VE    |
| [111]     | Misery Scale (MISC)                   | 24 | Motion-sickness | 0–10         | 161       | 1    | VE    |
| [112]     | Symptom Questionnaire                 | 16 | Motion-sickness | 0–6          | 155       | 13    | VE    |
| [113]     | Refactored SSQ                        | 371 | Nausea, and Oculomotor | 4-point  | 140       | 16    | VE    |
| [107]     | Simplified Simulator Sickness Questionnaire | 158 | Uneasiness, Visual Discomfort and Loss of Balance | 5-point | 2       | 9    | CM    |

**Instrumental IMEx/HIFs assessment**

While subjective assessment methods aim to collect qualitative feedback from the users concerning their experiences, instrumental methods aim to measure them in a quantitative manner, thus allowing for easier replication and real-time (or quasi real-time) IMEx/HIFs monitoring. For example, behavioural measures can track the user’s facial expressions, movements, and eye gaze to monitor user reactions without the need for conscious introspection. Psycho-physiological methods, in turn, can be used to measure correlates of experience factors, such as engagement, attention, and cybersickness, to name a few. Commonly, instrumental methods rely on ground-truth labels obtained via subjective methods in order to build accurate and reliable models. Once the models are built, however, subjective methods are no longer required and real-time assessment can be achieved. With advances in sensor technology and wearable devices, instrumental methods are burgeoning. In the sections to follow, we present the findings from a survey of the literature spanning the years of 2015–2021, with particular focus placed on psycho-physiological methods, as the existing literature lacks a survey in this aspect.

**Behavioural methods**

With behavioural methods, the main goal is to assess whether the participants behave in the virtual environment as they would under similar conditions in the physical environment. For example, are the user’s physical movement and social interactions inline with those expected in the real world. Recent studies suggest that this can indeed be the case and participants can express verbal and bodily reactions in virtual reality in manners very similar to real situations [120]. Behaviors can provide unconscious cues about user experiences. A smile on one’s face typically indicates good user experience, while touching the HMD could imply poor fit or discomfort, and sweating and nausea typically indicates signs of cybersickness. In [121], for example, statistics showed that almost 50% of subjects touched their HMD at least once, suggesting discomfort and reduced sense of immersion. Over 76% of the participants, in turn, smiled at least once during the experiment, suggesting a positive reaction to the virtual content. Finally, roughly 10% of the participants reported sweating and nausea symptoms, suggesting visual fatigue and signs of motion sickness. The next sections report the various methods in which researchers have proposed to measure behaviours and what they represent in terms of IMEx.

© Springer
Facial expressions

Facial expressions can tell a lot about the current emotional state of the user. Moreover, real-time facial expression recognition can improve the realism of virtual avatars, which can play a key role in user experience [122]. Recent innovations in sensor-equipped VR headsets have allowed for facial expressions to be monitored via facial electromyogram (EMG) electrodes placed directly on the VR faceplate of the head-mounted display (HMD) [31]. Alternatively, stand-alone facial EMGs have been placed in a transparent adhesive plastic film identical in shape and size to the actual HMD and placed around the eyes prior to donning the HMD [123]. Such a system was used to recognize 11 different facial expressions and on a sample size of 42 participants, an average expression recognition rate of 85% was achieved with eight sensors.

Eye tracking

Eye tracking provides information not only on where the users are focusing their attention at any particular point in time, but also on pupil dilation, blink rates, and eye movements indicative of e.g., cybersickness. Indeed, increases in pupil size reflect arousal associated with increased sympathetic activity [124]. In [125], a stressful experiment was conducted and showed that pupil dilatation and heart rate changes showed differences with stress. Furthermore, eye blink rate has a close direct relationship with dopamine activity in the brain, hence could be related to valence [126]. Moreover, increased attention levels have been shown to reduce blink frequency [127], as have more positive affective states [124]. Eye gaze information has also been linked to concentration levels and sense of presence in immersive environments [128]. More recently, pupillometry (more specifically, pupil dilation) was used to assess cognitive load in VR with uncontrolled scene lighting [129].

Eye tracking can typically be achieved with infrared cameras embedded into the HMD. Alternatively, electrooculography (EOG) sensors could also be embedded directly into the VR headset, as in [31], and used to track eye movements [32] and blink rates. Real-time knowledge of where the user is looking can also provide virtual environment developers cues about what captures users’ attention, what elements were more calming or stressful, and can allow for adaptive systems to be developed to make experiences more realistic (e.g., have an avatar look at you when you look at them), hence maximizing IMEx. More recently, eye movement information has also been shown to correlate with cybersickness, where atypical eye movements were indicative of motion sickness [130].

Movements and gestures

Body and head movements, along with arm gestures can also be indicative of IMEx related factors. For example, the work in [131, 132] showed correlations between head movements and user reports of valence, arousal, and emotional states. The work in [133], in turn, showed that different types of head movements (i.e., rotations and left/right tilts) could affect cybersickness. Postural stability was also shown to predict the likelihood of cybersickness in [134] and constrained movement was shown to reduce the sense of presence [46]. Commonly, hand tracking and gesture recognition has relied on VR controllers equipped with sensors. More recently, camera based systems have emerged that have allowed for controller-free hand/arm gesture tracking. While intuitively one would expect the controller-free setting to be more realistic, hence improve the overall IMEx, a recent study showed that controller-based interactions in VR were less demanding for the participants and resulted in fewer errors, thus in an overall improved IMEx [135]. The authors attributed this finding to the camera-based technology still being in its infancy (hence, not very reliable) and the learning curve of the user’s to a new technology. The interested reader is referred to [136] for an overview of gesture interactions in VR.

Psycho-physiological methods

Our bodies are an excellent canvas to convey our internal states. For example, our faces turn red when we are embarrassed, our heart rates go up when we are excited and/or stressed, our palms become sweaty when we are nervous or suffering from motion sickness, our heart rates and breathing rates synchronize when we are engaged. As biosensor technologies evolve and wearable devices become mainstream, psycho-physiological measurement has become a reality and has been incorporated into instrumental IMEx/HIFs assessment. In the sections to follow, we highlight methods that have been proposed in the literature over the last six years separated by biosensor modality. As the existing literature lacks a comprehensive survey of such instrumental methods, we aim to fill this gap with this paper.

Electrocardiogram and photoplethysmogram

Electrocardiogram (ECG) and photoplethysmogram (PPG) have become increasingly popular for studies in immersive virtual environments where a user’s heart rate (HR) and heart rate variability (HRV) need to be measured. While an ECG records the electrical activity of the heart, a PPG measures blood volume changes using optical sensors that measure changes in light absorption. Both methods provide information about heart rate, with PPG being the most...
widely used modality in wearables, as sensors can be easily embedded into bracelets and watch form factors. In both methods, it is common for a so-called RR time series to be derived from the interbeat/interpulse intervals and HRV analysis is typically done on this heart rate series signal.

HRV analysis can be done in the time and frequency domains, as well as with nonlinear methods. Time-domain parameters rely on statistics computed directly from the RR series, such as standard deviation over certain window sizes. Frequency domain methods, in turn, rely on the power spectral density (PSD) of the RR time series, computed either via nonparametric (e.g., fast Fourier transform) or parametric (e.g., autoregressive models) methods. The PSD is then divided into different frequency bands, such as very low frequency (VLF: 0–0.04 Hz), low frequency (LF: 0.04–0.15 Hz), and high frequency (HF: 0.15–0.4 Hz), as these have shown to represent different aspects of the sympathetic and parasympathetic autonomic nervous systems. Commonly, absolute, relative, or normalized powers in the VLF, LF and HF bands, as well as their ratios, have been used to characterize heart rate variability. Lastly, as the RR time series exhibits complex non-linear behavior, non-linear measures have also been explored [137].

Table 4 presents a list of studies that have relied on HR and HRV measures to quantify different aspects of IMEx. As can be seen, measurement of stress is one of the leading aims. Dependent on the difficulty level of the game or the stressful sequences, an increase of HR is commonly observed [138, 139]. Moreover, a significant correlation between the valence emotional primitive and HRV has been demonstrated [140, 141]. An increase in HR was also seen during the last minutes when the user reported motion sickness [142]. The majority of the devices used were wearables-based, thus allowing the user to move during the immersive VR experience. It should also be noted that in the majority of the cases, multimodal systems were utilized, with HR/HRV coupled with other modalities; electrodermal activity (EDA) being the most prevalent [139, 140, 143–149]. The next sub-section is dedicated to the measurement IMEx correlates from the EDA.

Electrodermal activity

Electrodermal activity (EDA), also known as galvanic skin response (GSR), measures the variation of the electrical conductance of the skin in response to sweat secretion. In the past, EDA has been associated with various aspects of psychological functioning, such as mechanisms underlying attention, information processing, emotion and stress. Several methods can be used to measure EDA, but a typical procedure consists of applying a constant voltage between two electrodes (commonly placed on the fingers, but also possible in other parts of the body, such as wrists and feet) to record conductivity variations, expressed in microsiemens (μS). Three types of electrodermal measures are commonly used [150]: skin conductance level (SCL), representing a baseline measure of electrodermal conductance; non-specific skin conductance responses (NS-SCRs), representing the frequency of spontaneous and momentarily changes in conductance, which are independent of external stimuli; and skin conductance responses (SCRs), which are momentary changes, similar to the NS-SCRs, but specifically elicited by external stimuli.

Table 5 lists the works that have relied on EDA signals for IMEx-related assessment. As can be seen, SCL peaks and amplitudes (and statistical measures over time) have been used to assess user experience, presence, and emotions. In particular, high sense of presence has shown to result in significantly more EDA peaks per minute than environment elicitig lower sense of presence [151]. Moreover, slow and steady increases in SCR have been shown to be correlated with cognitive activity [148]. EDA can also be attributed to an increase in mental workload or stress, as well as as significantly positively correlated with arousal states [124]. Lastly, during cybersickness events, researchers were able to observe a positive relationship between EDA responses and high jerk effects [145].

Electroencephalograms

Electroencephalograms (EEG) measure electrical activity of the cortex using electrodes placed on the scalp. EEGs can be used to measure (cortical) neural activity in different parts of the brain, as well as connectivity patterns between different brain regions, which could be indicative of different affective states [152]. In fact, so-called affective EEG brain-computer interfaces have been used to model human influential factors for speech QoE modeling [24].

In recent years, several studies have explored the use of EEG for IMEx-related research. Tables 6 and 7, for example, list studies that have used different EEG features as correlates of IMEx parameters and cybersickness, in particular, respectively. As can be seen, event-related potential (ERP), ratio between the event-related desynchronization (ERD) and event-related synchronziation (ERS), and statistical features such as the mean, the power of all frequency bands, and even the standard deviation of the EEG time series have been explored. EEG electrodes are typically positioned in the frontal, parietal, central, occipital, and temporal areas. Researchers have observed strong significant correlations between the subjective experience of presence and (i) the N1 ERP component (a large negative peak occurring roughly 80–120 ms post visual stimulus presentation) and (ii) the mismatch negativity (MMN), an ERP component resulting from the presentation of an odd stimulus in a sequence of stimuli, regardless of whether the subject is paying attention.
| Reference | # Subjects | Device | Measurement | Processing | Results | Questionnaire |
|-----------|------------|--------|-------------|------------|---------|---------------|
| [138]     | 21         | AliveCor Kardia | Engagement, Concentration, Stress, Relaxation, and Emotion | HR | A low HR for Relaxation, an elevated HR for concentration, and an increase of HR during stress | PQ, and SUS |
| [162]     | 60         | MP30 from Biopac System | Stress | Average of LF/HF ratio | Significant differences in the average ratios of LF/HF, as a function of plan configuration | Not applicable |
| [143]     | 18         | e-Health Sensor Platform V2.0 | QoE in terms of Quality, Frame-rate and Texture | Statistical features from HR: mean, min, max, median, std; | For Quality, no impact on the physiological responses | ACR, and SSQ |
| [144]     | 20         | E4 from Empatica | Presence | Statistical features from HR: mean, LF, HF; | ECG features did not significantly vary between the presence and lack of factors of presence | PQ |
| [145]     | 33         | g.USBamp and g.TRIGbox from g.tec | Mental immersion | Mean HR, and HRV; | HRV turned out to be significantly affected by network condition. Significant relationships between HRV and IEQ and gaming QoE | IEQ, Gaming QoE, and Video quality |
| [158]     | 10         | Polar H10 | User Experience | HRV, Time elapsed between two successive R-waves of the QRS signal (R-to-R interval), HF, LF, and VLF | HR and HRV are significantly different during resting once compared with the easy, medium, and hard difficulties | SSQ, Simulation performance, and Post-session interview |
| [146]     | 24         | E4 from Empatica | Emotional responses | Mean HR, and std HR, root square of R-to-R, LF, and HF; | Higher classification accuracy of cognitive load against the HR data of 82.78% | Not applicable |
| [139]     | 24         | ProComp Infinity from T &T | Gaming experience | Mean HR, and LF/HF ratio | All considered measures reported statistically significant increases due to playing in VR, | Demographics, System Usability Score, Visual Analogue Scale; SUS PQ |
| [147]     | 49         | Brainproducts V-AMP 16 | Fear effect on presence | Mean HR | Physiological responses in virtual heights leads to higher presence | Acrophobia Questionnaire, State-trait Anxiety Inventory, SSQ, MEC spatial, and PQ |
| [163]     | 33         | E4 from Empatica | Influence of jerk on cybersickness | Inter-beat interval; HR | Lower HR with a high jerk effect. Correlation between HRs during collision periods and SS scores | IPQ, System Usability Scale, NASA task load assessment, SAM, and SSQ |
| [148]     | 600        | Fitbit Charge | QoE | HR | A minor increase is noted in the tablet group as the mean HR increases by 1.8% over the test duration. The VR group experienced a slightly larger increase of 3.33%. Lastly, the AR group experienced the highest increase of 5.7% | Post-Test Questionnaire; video quality, audio quality, and audiovisual quality Questionnaire |
to the sequence or not [151]. Moreover, the total band power (1–45 Hz) in the frontal and frontal-left regions decreased with sense of presence and relative beta (16–30 Hz) and delta (below 4 Hz) powers increased in temporal and temporal right regions, respectively [144].

EEGs have also been used to measure arousal states while in VR, especially via the use of the so-called frontal alpha (8–15 Hz) asymmetry index [153]. Alpha power changes were also seen with changes in attention levels in a target-response paradigm [154, 155]. Moreover, the ratios of theta (4–8 Hz), alpha and beta were used to assess alertness levels [156]. In [140], in turn, a fearful experiment showed significant correlations between arousal and the higher end of the gamma band powers and between arousal and (lower end) beta band power; the sensation of fear was shown to be correlated with the power in the lower end of the gamma band. In turn, dominance was shown to be correlated with theta band power. When fear was not induced valence, arousal, and dominance levels showed some correlations but only with the higher end of the gamma frequency band. Correlates of engagement in VR have also been proposed and they typically correspond to the ratio of the beta frequency band power (16–30 Hz) to the combined power in the alpha and theta ranges (4–15 Hz) [157, 158]. Lastly, the measurement of cybersickness using EEG has been proposed recently and deep neural network classifiers have been explored [159]. A sickness index relying on alpha, theta, and beta frequency subbands showed to achieved 84% in detecting cybersickness [160, 161].

In order to better understand the role of each brain region shown to correlate with sense of presence, some researchers have relied on functional magnetic resonance imaging or functional near-infrared spectroscopy to get a snapshot of which brain regions become active while in VR. In [165], for example, frontal, parietal and occipital regions showed involvement during free virtual navigation and activation in the dorsolateral prefrontal cortex was shown to be negatively correlated to sense of presence, hence corroborating some of the EEG findings. In turn, brain regions responsible for balance and vestibular (located in the cerebellum) inputs were shown to be active during cybersickness events [166].

### Multiple-sensorial media applications

The majority of current applications stimulate only one (visual) or two senses (audio-visual). As the tactile Internet and Internet of Senses revolutions emerge, additional senses will be stimulated, including olfactory and somatosensory. Such media has been termed multiple-sensorial media, or mulse-media, and within a VR framework, could lead to next-generation immersive systems with increased sense of realism and immersion [9, 167]. For example, inclusion of smells [168, 169] and haptics [170] have shown to improve sense of
| Reference | # Subjects | Device | Measurement | Processing | Results | Questionnaire |
|-----------|------------|--------|-------------|------------|---------|---------------|
| [143]     | 18         | e-Health Sensor Platform V2.0 for Arduino and Raspberry Pi | QoE in terms of Quality, Frame-rate and Texture Presence | Peaks detection | For quality: no impact on the physiological responses | ACR, and SSQ |
| [144]     | 20         | E4 from Empatica | Presence | Tonic and phasic decomposition | EDA features did not significantly vary between the presence and lack of factors of presence | PQ |
| [145]     | 30         | g.USBamp, g.TRIGbox from g.tec hardware | Mental immersion | Peaks and amplitude in Skin Conductivity | No significantly effect of network condition and screen size on skin conductivity | IQE, Gaming QoE, and Video quality |
| [146]     | 24         | E4 from Empatica | Emotional responses | Mean, std, peak, strong peak, 20th percentile, 80th percentile, quartile deviation | EDA classification has returned low accuracy | Not defined |
| [139]     | 24         | ProComp Infinity from T &T | Gaming experience | Skin conductance response (SCR) | Effect size revealed a large SCR | Demographics, System Usability Score, Visual Analogue Scale; SUS, and PQ |
| [147]     | 49         | Brainproducts | Fear effect on presence | SCL | Physiological responses in virtual heights leads to higher presence | Acrophobia Questionnaire, State-trait Anxiety Inventory, SSQ, MEC spatial, and PQ |
| [163]     | 33         | E4 from Empatica | Influence of jerk on cybersickness | Amplitude of SCR | Positive EDA responses with a high jerk effect | IPQ, System Usability Scale, NASA task load assessment, SAM, and SSQ |
| [148]     | 600        | Pip Biosensor | QoE | SCL | Slow and steady increase in SCR can be correlated with an increase in cognitive activity, EDA can be attributed to an increase in mental workload or stress | Post-Test Questionnaire; video quality, audio quality and audiovisual quality Questionnaire |
| [124]     | 18         | Shimmer3 Consensys | Determining affective responses | Skin conductance | Conductivity is significantly positively correlated with Arousal | Physical Activity Readiness Questionnaire (PAR-Q) |
| [151]     | 34         | Shimmer3 | Presence in video games | EDA amplitude and peak | High presence group had significant more EDA peaks/min than the low presence group | Demographics, MPS, SAM, and Emotional experiences questionnaire |
| [140]     | 24         | Not defined | Emotions | Median and its variation | Fear situation: arousal is correlated with median of EDA | Pre-test questionnaire, UES, SAM |
| [149]     | 31         | NeuLog EDA | Cybersickness | Average, percentage of change, min, and max of EDA | CNN-LSTM model can detect and predict cybersickness only the last two minutes of data with an accuracy of 97.44% and 87.38% | SSQ |
| Reference | # Subjects | Device | Electrode location | Measurement | Processing | Results | Questionnaire |
|-----------|------------|--------|--------------------|-------------|------------|---------|---------------|
| [153]     | 36         | 8 channels LXE5208 | Fp1, Fp2, F3, F4 | Presence on affective responses and attitude | Arousal = Absolute $\beta$ wave during stimulus - Absolute $\beta$ wave during rest; level of arousal: Band-to-band $\beta$ power | Increase in presence positively affected physiological arousal. Significantly higher arousal and attitude towards luge. | Not defined |
| [151]     | 34         | Advanced Brain Monitoring | Fz, F3, F4, Cz, C3, C4, POz, P3 and P4 | Presence in video games | ERPv | Strong significant correlation between the subjective experience of presence and the early ERP components of N1 and MMN | Demographics, MPS, SAM, and Emotional experiences questionnaire |
| [157]     | 25         | Mindwave | Fp1 | Patient engagement | Banpowers; Engagement index: absolute power of $\beta/(\alpha + \theta)$ | $\theta$ power in simulation conditions correlated with PQ scores to measure engagement an Increase of $\theta$ power and a decrease in $\alpha$ power | PQ |
| [158]     | 10         | Biocybernetic Loop Engine | TP9, Fp1, Fp2, and TP10 | Stress level | Absolute bandpowers; Engagement index; Frontal asymmetry index | Frontal $\theta$ values were significantly different between easy and hard difficulty levels | SSQ, Simulation performance, and Post-session interview |
| [138]     | 21         | MyndPlay BrainBand | Fp1 | User engagement, Concentration, Stress, Relaxation, and Level of emotion | Mean $\alpha$, $\beta$, and $\theta$ | An elevated $\theta$ level and reduced $\alpha$ level for stress, and an elevated $\alpha$ level for relaxation, an elevated $\beta$ level for concentration/focus, | PQ, and SUS |
| [199]     | 12         | BrainVision 32 channel amplifier system | Fp1/2, F7/8, F3/4, Fz, F1/2, FC3/4, T7/8, C3/4, Cz, TP7/8, CP3/4, CPz, P7/8, P3/4, Pz, O1/2, Oz and referenced to FCz | Spatial Presence | Eye blinks and muscles artefacts removal. Power of the $\alpha$ band, (ERD/ERS) = [{(bandpower reference x band power test)/(band power reference)}] x 100. | Strong spatial presence experiences are associated with increased ERD (cortical activity) in parietal/occipital areas of the brain together with decreased activity in frontal structures | Annett handedness questionnaire, and MEC-SPQ |
| Reference | # Subjects | Device | Electrode location | Measurement | Processing | Results | Questionnaire |
|-----------|------------|--------|-------------------|-------------|------------|---------|---------------|
| [140]     | 24         | Not defined | Not defined | Emotions   | Median for all EEG bands | With Fear case: significant correlation between arousal and high $\gamma$ and low $\beta$ band and sensation of fear with low $\gamma$ band. Dominance is correlated with $\theta$ band. No fear case: user’s valence, arousal, and dominance, all of them with HighGamma band |
| [144]     | 20         | g.Hlamp amplifier with the g.GAMMAcap2 EEG cap and g.SCARABEO active electrodes | F3, F4, T7, C3, C4, T8, P3, P4, PO7, PO8 | Presence | Mean of EEG signal, Std of EEG signal, Signal power all frequency bands, Asymmetry index | band power in the frontal and frontal-left regions were decreased. The relative $\beta$ and $\delta$ powers shows a significant increase in temporal and temporal right regions respectively | PQ |
| [200]     | 15         | Neuroelectrics Enobio 32 using 8 gel-based AgCl electrodes | Fpz, F3, F4, Fz, P3, P4, Pz, Oz | Presence, Engagement, and Immersion | $\alpha$ and $\theta$ band power in frontal and parietal EEG | Increased $\alpha$ and $\theta$ band power following the VR exposure, $\theta$ band power significantly higher compare to baseline, $\alpha$ power increase reached statistical significance in the initial phase | NASA-TLX, and VR UX |
### Table 7  List of works relying on EEG measurement for cybersickness assessment

| Reference | # Subjects | Device | Electrode location | Measurement | Processing | Results | Questionnaire |
|-----------|------------|--------|-------------------|-------------|------------|---------|---------------|
| [159]     | 130 (65M, 65F) | Neurosky Mindwave Mobile | Fp1 | Cybersickness | Low α, high α, low β, high β, θ, δ, low γ, and high γ waves, sickness detection including attention and meditation, and the sickness index: 2α+δ+θ+γ as input of binary LSTM network | Around 84% of accuracy for a window of 1, 5, and 10 mins | Not applicable |
| [201]     | 25         | Emotiv Epoc+ | AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 | Cybersickness | Image generation process of EEG data for an input to the CNN and DNN algorithms | Both algorithms gave 98% accuracy | Not applicable |
| [202]     | 202        | Not defined | Fp1, Fp2, F3, F4, T3, T4, P3, P4 | Cybersickness | Inter-correlation of the EEG channels and intra-correlation over the spectral and temporal information in each spectrogram as an input to a CNN | 87% accuracy | SSQ |
| [203]     | 44         | Emotiv Epoc EEG | AF3, AF4, F3, F4, F7, F8, FC5, FC6, T7, T8, P7, P8, O1, O2 | Cybersickness | EEG spectral power | Increase in spectral power, with respect to a baseline recording, is indicative of the onset of cybersickness | SSQ |
| [161]     | 18         | OpenBCI system | FP1, FP2, C3, C4, P3, P4, O1 and O2 | Cybersickness | Wavelet packet transform for EEG rhythm energy ratios of δ, θ, α and β | The average cybersickness recognition accuracy for single subject reaches 92.85%, and the cybersickness recognition accuracy to 18 subjects is also up to 79.25% | Not applicable |
| [160]     | 28         | 64-channel cap from AntNeuro | 64-channel | Cybersickness | Relative power of each frequency band | Beta and LG showed significance only for the individuals suffering from headache, fullness of head, and blurred vision, while no other significances were found for an EEG parameter | MSSQ |
immersion. Haptics can be used to provide the user with cues about physical characteristics of an object (e.g., weight or texture) hence increase sense of realism [171, 172]. Vibrotactile feedback, in turn, provides feedback when interacting with virtual devices [173], thus also improving the sense of realism [174]. Table 8 lists some of the emerging work on mulsemia QoE assessment via psycho-physiological methods. As an example, when using haptic gloves, a strong amplitude modulation or ERP signals occurred when the participants selected virtual objects and significant changes in the early negativity component of the ERP was seen during situations with haptic conflicts [175]. Moreover, while addition of olfactory stimuli showed a significant increase in sense of presence, it did not generate significant changes in EDA [176], hence suggesting that alternate modalities may be needed. It is important to emphasize that while our search period encompassed papers from 2015 to 2021, a great number of works in the mulsemia domain appeared prior to 2015. The interested reader could refer to [177] for a detailed review of mulsemia systems proposed prior to 2015.

Concluding remarks and suggestions for future work

Monitoring of human behaviour and psycho-physiological signals while immersed in virtual reality will allow models of human influential factors to be built, including to e.g., detect and even predict cybersickness, monitor the user’s perception of immersion and sense of presence, as well as overall immersive media experience. Ultimately, this information will allow for virtual environments and applications to be adjusted per user, thus maximizing the user experience. As emphasized by [178], the success or failure of any system for immersive communication will rely on the user experience that it provides and not necessarily on the technology it uses. Building IMEx systems that take into account system, context and human influential factors will be crucial for the development of the field.

Today, the most widely used measure of user IMEx remains subjective assessment. While subjective assessment can directly target specific IMEx dimensions (e.g., presence, immersion, cybersickness) with high validity, it requires offline evaluation, can be biased by subject responses [179], can be disruptive to the user experience with constant prompts, which, in turn, can increase the user’s cognitive load and indirectly affect the experience. Disruptions to answer subjective questionnaires can break the immersive experience and studies have reported that it can take some time before the sense of immersion is recovered post interruption [180]. Moreover, while VR-based questionnaires have been developed to replace paper-and-pencil ones (e.g., [33, 34]), their validity over time has yet to be confirmed. Future studies should explore this.

Furthermore, it is known that VR sickness drastically hampers IMEx. Studies have reported that women and children are more susceptible to cybersickness than men [181, 182], mostly due to a poor fit of their interpupillary distance to the VR headset [183]. More recently, an effect of smoking has also been reported [184]. While exposure and habituation can drastically reduce the prevalence and severity of cybersickness symptoms [185], especially over multiple sessions [186], getting through the first 20 min is crucial [187]. As such, being able to predict cybersickness at the beginning of a VR session could allow for mitigation strategies to be put in place “on the fly”, such as bringing in additional sensory modalities [188], hence improving the overall IMEx. Psycho-physiological measures are crucial for such real-time cybersickness evaluation. As shown here, however, only few works exist that have focused on cybersickness prediction, hence there is ample room for research. In particular, the methods relying on EEG signals have all used stand-alone EEG systems worn under the VR headset. This could lead to discomfort, hence indirectly affecting the IMEx. Future works should explore tools with sensors directly embedded into the VR headset, such as [31], where improved usability has been reported [189]. Moreover, the developed tools have mostly relied on deep neural networks, which could be power and storage hungry, thus not suitable for untethered applications in which the user is truly mobile. As such, future work should explore the use of feature engineering to find more robust features that can be coupled with simpler machine learning algorithms, as shown in [190].

As 5G and 6G wireless communications become more widespread, truly portable VR applications are emerging where the user is completely mobile and untethered to a computer [191]. Movement is known to generate artifacts that affect psycho-physiological signal quality and hamper human influential factors assessment. Existing enhancement algorithms, however, especially those developed for EEG signals, have not been tailored to such artifacts [192], hence new algorithms and movement artifact robust features will need to be developed. Adaptive systems are already starting to emerge (e.g., [193]) but further work is needed. Moreover, multimodal systems have shown to be useful in such mobile conditions where multiple signal modalities can account for certain confounding factors (e.g., fatigue on HRV) [194], but such systems within a portable immersive application are still needed to learn what confounding factors exist within an IMEx (e.g., how does fatigue effects on HRV affect the presence-related HRV features?). Future work should focus on better understanding these confounds.
And as wireless communication bandwidths and coverage increase, and latency decreases, future generation technologies, such as the tactile internet [195] or the Internet of Senses [196] will become the mainstream. In such scenarios, multiple senses will be stimulated, including olfactory, taste, and somatosensory systems, hence drastically improving the IMEx. As highlighted in [188], smells have already been explored and shown to reduce cybersickness symptoms, as have pleasant songs. Haptic feedback, in the form of vibrations and airflow time-aligned with visual cues, have also helped increase overall experience. The effect that such multisensory stimuli has on behavioural and psycho-physiological signals is still not well understood and only a few works have explored this direction (see Table 8). Future work should focus on multi-sensorial media and the overall impact it has on IMEx, including possible timing mismatch between different modalities.

Lastly, as highlighted by [5], IMEx is multi-faceted. Most of the works surveyed have touched only one or a few of the influential factors, hence only show a snapshot of what can be achieved with IMEx assessment. Recently, a unified user experience questionnaire was proposed containing 10 sub-scales to measure presence, engagement, immersion, flow, usability, skill, emotion, experience consequence, judgement, and technology adoption [93]. Future studies should explore the use of behavioural and psycho-physiological metrics to measure each of these components and measure their individual contributions to overall IMEx. Initial steps in this direction have been taken for speech (e.g., [24]), image [197], and video applications [198] where more than

| Articles  | # Subjects | Modality | Sense | Device | Measurement | Processing | Results | Questionnaire |
|-----------|------------|----------|-------|--------|-------------|------------|---------|--------------|
| [204]     | 27         | ECG, EDA | Olfactory, Haptics, Thermal, Wind | Ambiotherm | Presence | HR, and SCL | A rise in HR was observed at the onset of the different wind/thermal stimuli and towards the end of the olfactory stimuli. Higher EDA values, which represent high arousal, have been noted to correlate with Negative Affect | Game experience Q, and PQ |
| [176]     | 60         | EDA      | Olfactory | Mindware MW3000A, Dreamreapers Inc. | Augment the exposure therapy process | Event related SCR | Olfactory stimuli increase presence but not EDA | IPQ, Quick Smell Identification Test, State-Trait Anxiety Inventory, Immersive Tendencies Questionnaire, Presence Visual-Analogue Scale |
| [175]     | 11         | EEG      | Haptics gloves | Model308-100, Brain-Products 64 chan | Detect conflicts in visuo-haptic sensory integration | ERPs | Strong amplitude modulation occurring when selection of objects; The early negativity component of the ERP is more pronounced during situations with haptic conflicts | Not applicable |

Table 8 List of works using psycho-physiological measurements to assess QoE of immersive multimedia applications
one influential factor has been explored and combined. Limited work exists, however, with immersive and multimeida applications. Future work should aim to fill this gap.

**Declarations**

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

**References**

1. Research ZM (2019) Augmented and virtual reality market by device, application, and vertical: global industry perspective, comprehensive analysis, and forecast, 2018–2025. GlobeNewswire

2. Gilbert N (2022) 74 virtual reality statistics you must know in 2021/2022: adoption, usage & market share. https://financeson line.com/virtual-reality-statistics/. Accessed 2022-03-09

3. Apostolopoulos JG, Chou PA, Culbertson B, Kalker T, Trott MD, Wee S (2012) The road to immersive communication. Proceedings of the IEEE 100(4):974–990

4. Brunnström K, Beker SA, De Moor K, Dooms A, Dooms A, Garcia M-N, Hossfeld T, Junisko-Pyykkö S, Keimel C, Larabi M-C, Lawlor B, Le Callet P, Möller S, Pereira F, Pereira M, Perkins A, Pibernik J, Pinheiro A, Raake A, Reichl P, Reiter U, Schatz R, Schelkens P, Skorin-Kapov L, Strohmeier D, Timmerer C, Varela M, Wechsel I, You J, Zgank A (2013) Qualinet White Paper on Definitions of Quality of Experience, qualinet White paper on Definitions of Quality of Experience Output from the fifth Qualinet meeting. Novi Sad, March 12, 2013

5. Perkins A, Timmerer C, Baraković S, Baraković J, Bich S, Bosse S, Botev J, Brunnström K, da Silva Cruz L, Moor KD, de Polo Saibanti A, Durnez W, Egger-Lampl S, Engelke U, Falk TH, Hameed A, Hines A, Jumisko-Pyykkö S, Keimel C, Larabi M-C, Lawlor B, Le Callet P, Möller S, Pereira F, Pereira M, Perkins A, Pibernik J, Pinheiro A, Raake A, Reichl P, Reiter U, Schatz R, Schelkens P, Skorin-Kapov L, Strohmeier D, Timmerer C, Varela M, Wechsel I, You J, Zgank A (2013) Qualinet White Paper on Definitions of Quality of Experience, qualinet White paper on Definitions of Quality of Experience Output from the fifth Qualinet meeting. Novi Sad, March 12, 2013

6. Berkman MI, Akan E (2019) Presence and immersion in virtual reality. In: Encyclopedia of computer graphics and games

7. Kharoub H, Lataifeh M, Ahmed N (2019) 3D user interface design and usability for immersive vr. Appl Sci 9:4861

8. Kim Y, Rhii I, Rhie M, Choi H, Yun M (2019) Current state of user experience evaluation in virtual reality: a systematic review from an ergonomics perspective. In: Proceedings of the human factors and ergonomics society annual meeting, vol 63, pp 1274–1275

9. Daniele F, Lecuyer A, Guilhotel P, Fleureau J, Mollet N, Christie M (2013) Enhancing audiovisual experience with haptic feedback: a survey on h. IEEE Trans Haptics 6(2):193–205

10. Schuermie M, Straaten P, Krijn M, Mast C (2001) Research on presence in virtual reality: a survey. Cybropsychol Behav 4:183–201

11. Usoh M, Catena E, Arman S, Slater M (2000) Using presence questionnaires in reality. Presence Teleoper Virtual Environ 9:497–503

12. Witmer BG, Singer MJ (1998) Measuring presence in virtual environments: a presence questionnaire. Presence 7(3):225–240

13. Inske B (2003) 7 measuring presence: subjective, behavioral and physiological methods. Being there: concepts, effects, and measurement of user presence in synthentic environments

14. Schwind V, Knierim P, Haas N, Henze N (2019) Using presence questionnaires in virtual reality. In: Proceedings of the 2019 CHI conference on human factors in computing systems, pp 1–12

15. Wiederhold B, Jang D, Kaneda M, Cabral I, Lurie Y, May T, Kim I, Wiederhold M, Kim S (2003) An investigation into physiological responses in virtual environments: an objective measurement of presence. In: Towards cyberpsychology: mind, cognitions and society in the internet age, pp 176–182

16. Crowley K, Slinity A, Pitt M, Murphy D (2010) Evaluating a brain-computer interface to categorise human emotional response. In: 2010 10th IEEE international conference on advanced learning technologies, pp 276–278

17. Akhtar Z, Falk T-H (2017) Audio-modal multimedia quality assessment: a comprehensive survey. IEEE Access 5:21090–21117

18. Martinez Rodrigo A, Garcia B, Alcaraz R, González P, Fernández-Caballero A (2018) Multiscale entropy analysis for recognition of visually elicited negative stress from eeg recordings. Int J Neural Syst 29:1850038

19. Dehais F, Dupres A, Di Flumeri G, Verdiere K, Borghini G, Babiloni F, Roy R (2018) Monitoring pilot’s cognitive fatigue with engagement features in simulated and actual flight conditions using an hybrid fms-eeg passive bci. In: 2018 IEEE international conference on systems, man, and cybernetics (SMC). IEEE, pp 544–549

20. Clerico A, Tiwari A, Gupta R, Jayaraman S, Falk T (2018) Electroencephalography amplitude modulation analysis for automated affective tagging of music video clips. Front Comput Neurosci 11:115

21. Weech S, Kennes S, Barnett-Cowan M (2019) Presence and cyber-sickness in virtual reality are negatively related: a review. Front Psychol 10:158

22. Burns C, Fairclough S (2014) Use of auditory event-related potentials to measure immersion during a computer game. Int J Hum Comput Stud 73:107–114

23. Egam D, Brennan S, Barrett J, Qiao Y, Timmerer C, Murray N (2016) An evaluation of heart rate and electrodermal activity as an objective qoe evaluation method for immersive virtual reality environments. In: 2016 Eighth international conference on quality of multimedia experience (QoMEX). IEEE, pp 1–6

24. Gupta R, Laghari K, Batville H, Falk TH (2016) Using affective brain–computer interfaces to characterize human influential factors for speech quality-of-experience perception modelling. Human-centric Comput Inf Sci 6(1):1–19

25. Patrão B, Pedro SL, Menezes P (2016) Human emotions and physiological signals: a classroom experiment. Int J Online Eng 12:37–39

26. Škalvečič J, Damaščević R, Maskeliunas R, Laukienė I (2019) Anxiety level recognition for virtual reality therapy system using physiological signals. Electronics 8(9):1039

27. ur Rehman Laghari K, Gupta R, Arndt S, Antons J-N, Schleicher R, Möller S, Falk TH (2013) Neurophysiological experimental facility for quality of experience (qoe) assessment. In: 2013 IFIP/IEEE international symposium on integrated network management (IM 2013), pp 1300–1305

28. Lee S, Shin Y, Kumar A, Kim M, Lee H-N (2018) Dry electrode-based fully isolated EEG/fNIRS hybrid brain-monitoring system. IEEE Trans Biomed Eng 66(4):1055–1068

29. Kam J, Griffin S, Shen A, Patel S, Hinrichs H, Heinze H-J, Deouell L, Knight R (2018) Systematic comparison between a
wireless EEG system with dry electrodes and a wired EEG system with wet electrodes. NeuroImage 184: 09
30. Arad E, Bartsch R, Kantelhardt J, Plotnik M (2018) Performance-based approach for movement artifact removal from electroencephalographic data recorded during locomotion. PLoS ONE 13:e0197153
31. Cassani R, Moinnereau M-A, Ivanscu L, Rosanne O, Falk T (2020) Neural interface instrumented virtual reality headset: toward next-generation immersive applications. IEEE Syst Man Cybern Mag 6(3):20−28
32. Moinnereau M-A, Oliveira A, Falk TH (2020) Saccadic eye movement classification using eeg sensors embedded into a virtual reality headset. In: 2020 IEEE international conference on systems, man, and, cybernetics (SMC). IEEE, pp 3494−3498
33. Schwind V, Knerim P, Chuang L, Henze N (2017) “where’s pinky?” the effects of a reduced number of fingers in virtual reality. In: Proceedings of the annual symposium on computer-human interaction in play, vol 10, pp 507−515
34. Schwind V, Knerim P, Tasci C, Franczak P, Haas N, Henze N (2017) “these are not my hands!” effect of gender on the perception of avatar hands in virtual reality. In: Proceedings of the 2017 CHI conference on human factors in computing systems, pp 1577−1582
35. Regal G, Schatz R, Schrammel J, Suette S (2018) Vrate: a unity3d asset for integrating subjective assessment questionnaires in virtual environments. In: 2018 Tenth international conference on quality of multimedia experience (QoMEX), pp 1−3
36. Feick M, Kleer N, Tang A, Krüger A (2020) The virtual reality questionnaire toolkit. In: AP UIST 2020: adjunct proceedings of the 33rd annual ACM symposium on user interface software and technology, UIST 2019
37. Jerald J (2015) The VR book: human-centered design for virtual reality. Morgan & Claypool, San Rafael
38. Sanchez-Vives M, Slater M (2005) From presence to consciousness through virtual reality. Nat Rev Neurosci 6:332−339
39. Slater M (2004) How colorful was your day? Why questionnaires cannot assess presence in virtual environments. Presence 13:484−493
40. Schubert T, Friedmann F, Regenbrecht H (2001) The experience of presence: factor analytic insights. Presence 10:266−281
41. Witmer A, Slater M (1999) Measuring presence: a response to the witmer and singer presence questionnaire. Presence (Camb) 8:560−565
42. Slater M, Steed A, McCarthy J, Mariangeli F (1998) The influence of body movement on subjective presence in virtual environments. Hum Factors 40:469−77
43. Usoh M, Arthur K, Whitton M, Bastos R, Steed A, Slater M, Brooks F, Jr (1999) Walking > walking-in-place > flying, in virtual environments. In: Proceedings of the 26th annual conference on computer graphics and interactive techniques ACM
44. Oh CS, Bailenson JN, Welch GF (2018) A systematic review of social presence: definition, antecedents, and implications. Front Robot AI 5:114
45. Servotte J-C, Goosse M, Campbell SH, Dardenne N, Pilote B, Simonneau IL, Guillaume M, Bragard I, Ghysen A (2020) Virtual reality experience: immersion, sense of presence, and cyber-sickness. Clin Simul Nurs 38:35−43
46. Riches S, Elghany S, Garety P, Rus-Calafell M, Valmaggia L (2019) Factors affecting sense of presence in a virtual reality social environment: a qualitative study. Cyberpsychol Behav Soc Netw 22(4):288−292
47. Gunawardena CN, Zittle FJ (1997) Social presence as a predictor of satisfaction within a computer-mediated conferencing environment. Am J Distance Educ 11(3):8−26
48. Grassini S, Laumann K (2020) Questionnaire measures and physiological correlates of presence: a systematic review. Front Psychol 11:349
49. Laarni J, Ravaja N, Saari T, Böcking S, Hartmann T, Schramm H (2015) Ways to measure presence. review and future directions. Immersed in media experiences: handbook of the psychology and design of presence in virtual environments. Lawrence Erlbaum Associates, Mahwah, NJ
50. Pianzola F (2021) Presence, flow, and narrative absorption questionnaires: a scoping review. Open Res Europe 1:11
51. Kim G, Biocca F (2018) Immersion in virtual reality can increase exercise motivation and physical performance. In: International conference on virtual, augmented and mixed reality. Springer, pp 94−102
52. Berta R, Bellotti F, De Gloria A, Pranantha D, Schatten C (2013) Electroencephalogram and physiological signal analysis for assessing flow in games. IEEE Trans Comput Intell AI Games 5:164−175
53. Kim YM, Rhiu I, Yun MH (2020) A systematic review of a virtual reality system from the perspective of user experience. Int J Hum Comput Interact 36(10):893−910
54. Barfield W, Weghorst S (1993) The sense of presence within virtual environments: a conceptual framework. Adv Hum Factors Ergonom 19:699
55. Hendrix C, Barfield W (1996) Presence within virtual environments as a function of visual display parameters. Presence Teleoper Virtual Environ 5(3):274−289
56. Johnson M, Foley M, Stengas A, Raye C (1989) Phenomenal characteristics of memories for perceived and imagined autobiographical events. J Exp Psychol Gen 117:371−376
57. Lombard M, Bolmarcich T, Villanova P, Crane D, Davis B, Gil-Egui G, Horvath K, Rossman J (2000) Measuring presence: a literature-based approach to the development of a standardized paper-and-pencil instrument. Book Measuring presence: a literature-based approach to the development of a standardized paper-and-pencil instrument
58. Kim T, Biocca F (1997) Telepresence via television: two dimensions of telepresence may have different connections to memory and persuasion. J Comput Med Commun 3(2):CMC325
59. Baños R, Botella C, Garcia-Palacios A, Martín H, Perpiñá C, Alcañiz Raya M (2000) Presence and reality judgment in virtual environments: a unitary construct? CyberPsychol Behav 3:327−335
60. Thie S, Wijk J (1998) A general theory on presence: experimental evaluation of social virtual presence in a decision making task. In: Presence in shared virtual environments workshop, vol 1, no 4
61. Parent A (1999) A virtual environment task-analysis tool for the creation of virtual art exhibits. Presence Teleoper Virtual Environ 8:355−365
62. Dinh HQ, Walker N, Hodges LF, Song Chang, Kobayashi A (1999) Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. In: Proceedings IEEE virtual reality (Cat. No. 99CB36316), pp 222−228
63. Murray C, Arnold P, Thornton B (2000) Presence accompanying induced hearing loss: implications for immersive virtual environments. Presence 9:137−148
64. Nichols S, Haldane C, Wilson JR (2000) Measurement of presence and its consequences in virtual environments. Int J Hum Comput Stud 52(3):471−491
65. Basdogan C, Ho C-H, Srinivasan MA, Slater M (2000) An experimental study on the role of touch in shared virtual environments. ACM Trans Comput Hum Interact 7(4):443−460
66. Lessiter J, Freeman J, Keogh E, Davidoff J (2001) A cross-media presence questionnaire: the itc-sense of presence inventory. Presence 10:282−297
67. Greef H, Ijsselsteijn W (2001) Social presence in a home tele-application. Cyberpsychol Behav 4:307–15
68. Gerhard M, Moore DJ, Hobbs DJ (2001) Continuous presence in collaborative virtual environments: towards a hybrid avatar-agent model for user representation. In: International workshop on intelligent virtual agents, pp 137–155
69. Krauss M, Scheuchenpflug R, Piechulla W, Zimmer A (2001) Measurement of presence in virtual environments. Experimentelle Psychologie im Spannungsfeld von Grundlagenforschung und Anwendung Proceedings, pp 358–362
70. Larsson P, Västfjäll D, Kleiner M (2001) The actor-observer effect in virtual reality presentations. Cyberpsychol Behav 4:239–246
71. Schroeder R, Steed A, Axelsson A-S, Heldal I, Abelin Å, Widström J, Nilsson A, Slater M (2001) Collaborating in networked immersive spaces: as good as being there together? Comput Graph 25(5):781–788
72. Bailerstein J, Rex C, Beall A, Loomis J (2001) Equilibrium theory revisited: mutual gaze and personal space in virtual environments. Presence Teleoper Virtual Environ 10:583–598
73. Tu C-H (2002) The measurement of social presence in an online learning environment. Int J e-learning 1:34–45
74. Biocca F, Harms C, Gregg J (2001) The networked minds and Anwendungsorientierte Psychologie im Spannungsfeld von Grundlagenforschung und Anwendung Proceedings, pp 358–362
75. Takatalo J, Häkkinen J, Kaistinen J, Nyman G (2007) Measuring user experience in digital gaming: theoretical and methodological issues. In: Proceedings of SPIE—the international society for optical engineering, vol 6494
76. Qin H, Rau P-L, Salvendy G (2009) Measuring player immersion in the computer game narrative. Int J Hum Comput Interact 25:107–133
77. Nowak K, Biocca F (2003) The effect of the agency and anthropomorphism on users’ sense of telepresence, copresence, and social presence in virtual environments. Presence Teleoper Virtual Environ 12:481–494
78. Cho D, Park J, Kim GJ, Hong S, Han S, Lee S (2003) The dichotomy of presence elements: the where and what. In: Proceedings of the IEEE virtual reality, 2003. IEEE, pp 273–274
79. Vorderer P, Wirth W, Gouveia F, Biocca F, Saari T, Jäncke L, Böcking S, Schramm H, Gysbers A, Hartmann T, Klimmt C, Laarni J, Ravaja N, Sacau A, Baumgartner T, Jäncke P (2004) Mec spatial presence questionnaire (mec-spq): short documentation and instructions for application. Report to the European Community. Project Presence: MEC (IST-2001-37661)
80. Lombard M, Ditton TB, Weinstein L (2009) Measuring presence: the temple presence inventory. In: Proceedings of the 12th annual international workshop on presence, pp 1–15
81. Thorson C, Grodzie B, Le H (2009) Predicting presence: constructing the tendency toward presence inventory. Int J Hum Comput Stud 67:62–78
82. Poeschl-Guenther S, Döring N (2013) The german vr simulation realism scale - psychometric construction for virtual reality applications with virtual humans. Stud Health Technol Inform 191:33–37
83. Makrinsky G, Lilleholt L, Aaby A (2017) Development and validation of the multimodal presence scale for virtual reality environments: a confirmatory factor analysis and item response theory approach. Comput Hum Behav 72:276–285
84. Tran HTT, Ngoc NP, Pham CT, Jung YJ, Thang TC (Oct 2017) A subjective study on qoe of 360 video for virtual communication. In: 2017 IEEE 19th international workshop on multimedia signal processing (MMSP), pp 1–6
85. Jennett C, Cox A, Dhoparee S, Epps A, Tijs T, Walton A (2008) Measuring and defining the experience of the immersion in games. Int J Hum Comput Stud 66:641–661
86. Sweetser P, Wyeth P (2005) Gameflow: a model for evaluating player enjoyment in games. Comput Entertain 3:3
105. Keshavarz B, Hecht H (2011) Validating an efficient method to quantify motion sickness. Hum Factors 53:415–426
106. Golding JF (2006) Predicting individual differences in motion sickness susceptibility by questionnaire. Pers Indiffer 41(2):237–248
107. Singla A, Göring S, Keller D, Ramachandra Rao RR, Fremerey S, Raake A (2021) Assessment of the simulator sickness questionnaire for omnidirectional videos. In: 2021 IEEE virtual reality and 3D user interfaces (VR), pp 198–206
108. Caseraman P, García-Agundez A, Zerban AG, Göbel S (2021) Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. Virtual Real 25:1153–1170
109. Saredakis D, Szpak A, Birckhead B, Keage HAD, Rizzo A, Loetscher T (2020) Psychometric evaluation of the simulator sickness questionnaire as a measure of cybersickness. PhD dissertation, Iowa State university. Front Hum Neurosci, vol 14
110. Gianaros P, Muth E, Mordkoff J, Levine M, Stern R (2001) A questionnaire for the assessment of the multiple dimensions of motion sickness. Aviat Space Environ Med 72:115–119
111. Bos J, Mackinnon S, Patterson A (2006) Motion sickness symptoms in a ship motion simulator: effects of inside, outside and no view. Aviat Space Environ Med 76:1111–1118
112. Ames S, Wolffsohn J, McBrien N (2005) The development of a symptom questionnaire for assessing virtual reality viewing using a head-mounted display. Opt Vis Sci 82:168–176
113. Bouchard S, Robillard G, Renaud P (2007) Revising the factor structure of the simulator sickness questionnaire. Annu Rev CyberTherapy Telemed 5:128–137
114. Bradley MM, Lang PJ (1994) Measuring emotion: the self-assessment manikin and the semantic differential. J Behav Ther Exp Psychiatry 25(1):49–59
115. Isomursu M, Taht M, Väinämö V, Kuutti K (2007) Experimental evaluation of five methods for collecting emotions in field settings with mobile applications. Int J Hum Comput Stud 65(4):404–418
116. Toet A, Hiejn F, Brouwer A-M, Mioch T, Erp J (2019) The EmoGrid as an Immersive Self-report Tool for the Affective Assessment of 360 VR Videos. Springer 10:330–335
117. Marín-Morales J, Higuera-Trujillo JL, Greco A, Guixeres J, Villani D, Gaggioli A, Botella C, Alcañiz M (2007) Affective computing in virtual reality: emotion recognition from brain and heartbeat dynamics using wearable sensors. Sci Rep 8(1):1–15
118. Riva G, Mantovani F, Capdeville CS, Preziosa A, Morganti F, Villani D, Gaggioli A, Botella C, Alcañiz M (2007) Affective interactions using virtual reality: the link between presence and emotions. Cyberpsychol Behav 10(1):45–56
119. Luong T, Lecuyer A, Martin N, Argelaguet F (2021) A survey on affective and cognitive VR. IEEE Trans Vis Comput Graph 1–20
120. Souza VCD, Nedel L, Kopper R, Maciel A, Tagliaro L (2018) The effects of physiologically-adaptive virtual environment on user’s sense of presence. In: 2018 20th symposium on virtual and augmented reality (SVR), pp 133–142
121. Yue K, Wang D, Yang X, Hu H, Liu Y, Zhu X (2016) Evaluation of the user experience of "astronaut training device": an immersive, vr-based, motion-training system. In: Optical measurement technology and instrumentation. International Society for Optics and Photonics, vol 10155, pp 99–105
122. Wirth M, Gradi S, Prosinger G, Kluge F, Roth D, Eskofer BM (2021) The impact of avatar appearance, perspective and context on gait variability and user experience in virtual reality. In: 2021 IEEE virtual reality and 3D user interfaces (VR), IEEE, pp 326–335
123. Cha H, Choi S, Im C (2020) Real-time recognition of facial expressions using facial electromyograms recorded around the eyes for social virtual reality applications. IEEE Access 8:62065–62075
124. Barathi SC, Proulx M, O’Neill E, Lutteroth C (2020) Affect recognition using psychophysiological correlates in high intensity vr exergaming. In: Proceedings of the 2020 CHI conference on human factors in computing systems, ser. CHI’20. Association for Computing Machinery, New York, NY, USA, pp 1–15
125. Hirt C, Eckard M, Kunz A (2020) Stress generation and non-intrusive measurement in virtual environments using eye tracking. J Ambient Intell Hum Comput 11:5977–5989
126. Dang L, Samanez-Larkin G, Castrellon J, Perkins S, Cowan R, Newhouse P, Zald D, (2017) Spontaneous eye blink rate (ebn) is uncorrelated with dopamine d2 receptor availability and unmodulated by dopamine agonism in healthy adults. eNeuro, 4:ENEURO.0211-17.2017
127. Takao M (2019) Immersive experience influences eye blink rate during virtual reality gaming. Polish Psychol Bull 50:49–51
128. Ju YS, Hwang JS, Kim SJ, Suk HJ (2019) Study of eye gaze and presence effect in virtual reality. In: Stephanidis C (ed) International 2019—Posters. Springer, Cham, pp 446–449
129. Eckert M, Habets EA, Rummukainen OS (2021) Cognitive load estimation based on pupillometry in virtual reality with uncontrolled scene lighting. In: 2021 13th International conference on quality of multimedia experience (QoMEX). IEEE, pp 73–76
130. Chang E, Kim HT, Yoo B (2021) Predicting cybersickness based on user’s gaze behaviors in hmd-based virtual reality. J Comput Des Eng 8(2):728–739
131. Li BJ, Bailenson JN, Pines A, Greenleaf WJ, Williams LM (2017) A public database of immersive vr videos with corresponding ratings of arousal, valence, and correlations between head movements and self report measures. Front Psychol 8:2116
132. Xue T, Ali AE, Ding G, Cesar P (2021) Investigating the relationship between momentary emotion self-reports and head and eye movements in hmd-based 360 vr video watching. In: Extended abstracts of the 2021 CHI conference on human factors in computing systems 2021, pp 1–8
133. Serge SR, Fragomeni G (2017) Assessing the relationship between type of head movement and simulator sickness using an immersive virtual reality head mounted display: a pilot study. In: International conference on virtual, augmented and mixed reality. Springer, pp 556–566
134. Arcioni B, Palmisano S, Apthorp D, Kim J (2019) Postural stability predicts the likelihood of cybersickness in active hmd-based virtual reality. Displays 58:3–11
135. Hameed A, Perks A, Möller S (2021) Evaluating hand-tracking interaction for performing motor-tasks in vr learning environments. In: 2021 13th International conference on quality of multimedia experience (QoMEX). IEEE, pp 219–224
136. Yang L, Huang J, Feng T, Hong-An W, Guo-Zhong D (2019) Gesture interaction in virtual reality. Virtual Real Intell Hardw 25:1153–1170
137. Tiwari A, Falk TH (2021) New measures of heart rate variability based on subband tachogram complexity and spectral characteristics for improved stress and anxiety monitoring in highly ecological settings. Front Signal Process 7:373881
138. Murphy D, Higgins C (2019) Secondary inputs for measuring user engagement in immersive vr education environments. arXiv: 1910.01586
139. Pallavicini F, Pepe A, Minissi ME (2019) Gaming in virtual reality: what changes in terms of usability, emotional response and sense of presence compared to non-immersive video games? Simul Gaming 50:136–159
140. Maia CLB, Furtado ES (2019) An approach to analyze user’s emotion in hci experiments using psychophysiological measures. IEEE Access 7:36471–36480
175. Gehrke L, Akman S, Lopes P, Chen A, Singh AK, Chen H-T, Lin C-T, Gramann K (2019) Detecting visuo-haptic mismatches in virtual reality using the prediction error negativity of event-related brain potentials. In: Proceedings of the 2019 CHI conference on human factors in computing systems, pp 1–11

176. Munyan BG, Neer SM, Beidel D, Jentsch F (2016) Olfactory stimuli increase presence in virtual environments. PLoS ONE 11:e0157568

177. Ghinea G, Timmerer C, Lin W, Gulliver SR (2014) Multisensorial: state of the art, perspectives, and challenges. ACM Trans Multimed Comput Commun Appl 11(1):1–23

178. Apostolopoulos JG, Chou PA, Culbertson B, Kalker T, Trott MD, Wee S (2012) The road to immersive communication. Proceedings of the IEEE 100(4):974–990

179. Janowski L, Pinson M (2015) The accuracy of subjects in a quality experiment: a theoretical subject model. IEEE Trans Multimed 17:1

180. Chung J, Gardner H (2012) Temporal presence variation in immersive computer games. Int J Hum Comput Interact 28:511–529

181. Gallagher M, Ferré E (2018) Cybersickness: a multisensory integration perspective. Multisensory Res 31:645–674

182. Andre L, Coutellier R (2019) Cybersickness and evaluation of a remediation system: a pilot study. In: 2019 International conference on 3D immersion (IC3D). IEEE, pp 1–6

183. Stanney K, Fidopiastis C, Foster L (2020) Virtual reality is sexist: but it does not have to be. Front Robot AI 7:4

184. Kim H, Kim JD, Chung WH, Park K-A, Kim JD, Kim D, Kim B (2021) Estimating cybersickness from related brain potentials. In: Proceedings of the 2019 CHI conference on human factors in computing systems, pp 1–13

185. Rosanne O, Albuquerque I, Gagnon J-F, Tremblay S, Falk TH (2021) Adaptive filtering for improved eeg-based mental workload assessment of ambulance users. Front Neurosci 15:341

186. Tiwari A, Cassani R, Gagnon J-F, Lafond D, Tremblay S, Falk TH (2020) Movement artifact-robust mental workload assessment during physical activity using multi-sensor fusion. In: 2020 IEEE international conference on systems, man, and cybernetics (SMC). IEEE, pp 3471–3477

187. Sharma SK, Wongang I, Anpalagan A, Chatzinotas S (2020) Toward tactile internet in beyond 5g era: recent advances, current issues, and future directions. IEEE Access 8:56948–56991

188. Shahzadi S, Iqbal M, Chaudhry NR (2021) 6g vision: toward future collaborative cognitive communication (3c) systems. IEEE Commun Mag Stand Mag 5(2):60–67

189. Farkkila T, Pomerantz Y, Laghari K, Möller S, Chau T (2012) Preliminary findings on image preference characterization based on neurophysiological signal analysis: towards objective qoe modeling. In: 2012 Fourth international workshop on quality of multimedia experience. IEEE, pp 146–147

190. Issa O, Speranza F, Falk TH et al (2012) Quality-of-experience perception for video streaming services: preliminary subjective and objective results. In: Proceedings of The 2012 Asia Pacific signal and information processing association annual summit and conference. IEEE, pp 1–9

191. Baumgartner T, Valko L, Esslen M, Jäncke L (2006) Neural correlate of spatial presence in an arousing and noninteractive virtual reality: an eeg and psychophysiology study. Cyberpsychol Behav 9:30–45

192. Skola F, Rizvić S, Cozza M, Barbieri L, Bruno F, Sklarlats F, Liarakopis F (2020) Virtual reality with 360-video storytelling in cultural heritage: study of presence, engagement, and immersion. Sensors 20:5851

193. Jeong D, Yoo S, Yun J (2019) Cybersickness analysis with eeg using deep learning algorithms. In: 2019 IEEE conference on virtual reality and 3D user interfaces (VR), pp 827–835

194. Kim J, Kim W, Oh H, Lee S, Lee S (2019) A deep cybersickness predictor based on brain signal analysis for virtual reality contents. In: 2019 IEEE/CVF international conference on computer vision (ICCV), pp 10579–10588

195. Krokos E, Varshney A (2021) Quantifying vr cybersickness using eeg. Virtual Real 2021:1–13

196. Ranasinghe N, Jain P, Thi Ngoc Tram N, Koh KCR, Tolley Wai Tung C et al (2018) Season traveller: Multisensory narrativising of the in-between. In: 2018 Tenth international conference on quality of multimedia experience. IEEE, pp 146–147

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.