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TOPICAL REVIEW

Scoping Review of Bioelectrical Signals Uses in Videogames for Evaluation Purposes

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ABSTRACT Bioelectric signals can improve assessment in videogames by helping to better understand user experience, evaluate attention, or study the cognitive and physical effects of games. Use of signals is therefore relevant to better evaluate and understand the impact and effects of videogames on players, and specially so in the field of serious games, such as educational or training games, to gain insights into the learning processes; or in games for health to better evaluate non-conscious effects on the player's body. We examine how biological signals (bioelectric + eye-tracking) are being used and collected in the field of video games, including the choice of signals, the devices used to collect them (e.g., wearables), the purposes for which they are collected, and the results reported from their use. As a result of this systematic literature review, 81 articles have been analyzed, finding that electrocardiograms and encephalograms are the most frequently used signals. The main use of these bioelectrical signals is to evaluate player engagement, level of difficulty, and stress during the gameplay. But there are also examples where signals are used to detect health problems, or as evidence to compare educational games with other learning activities. This review informs researchers interested in better understanding the benefits and limitations of biological signals for video games, providing an overview of studies conducted in recent years and the associated devices described in those studies. Limitations in this field include signal noise issues as well as the amount of time required to calibrate the devices during experiments, adding to the complexity of user testing. It is necessary to work on tools that facilitate experiments with large groups of users in parallel as well as to work on open software and low-cost devices that allow the emergence of a greater number of studies in this field, given for example their potential in the field of educational games to better understand the learning processes of users.

INDEX TERMS Assessment, biosignals, evaluation, serious games, videogames.

I. INTRODUCTION

The term biological signals or biosignal applies to all types of signals produced by living beings. Biosignals can be of different types, such as chemical or electric, and are usually generated involuntarily and therefore outside conscious control. Traditionally, the study of biosignals has been very important in medicine since they allow the diagnosis of diseases and health problems. Their use has now spread far beyond medicine. For example, uses of bioelectrical signals such as electroencephalography (EEG), electrodermal activity (EDA), electromyography (EMG) and electrocardiography (ECG) are being widely studied [1] and successfully applied in other fields such as neuroscience and neuromarketing [2], [3]. The extension of the use of these biosignals to other fields has been fostered by the emergence of new low-cost wearable devices that have lower requirements and are easier to use.

Biosignals have been applied to videogames, with several distinct goals: (1) to adapt games to their players (adaptive game) [4]; (2) to capture the emotional state of players (affective games), providing feedback to players regarding

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their state [5]; or (3) to allow players to interact with games using these signals (brain-computer interfaces as game controllers) [6]. Additionally, bioelectrical signal data can be analyzed to better understand the usage of the game, its non-conscious effects on the player and the extent to which players are engaged while playing. Thus, we can obtain objective feedback from users by interpreting reactions of their bodies through the signals being generated such as heart rate or brain activity. In turn, those bioelectrical signals can be used as evidence to improve user evaluation, making evaluations more objective and systematic while avoiding possible biases related to experimental approaches, such as those encountered when asking users to self-report engagement or emotional states.

Use of bioelectrical signals for evaluation purposes can be especially interesting in the field of serious games. The term serious game defines those games whose main purpose goes beyond entertainment [7]. Serious games have been used effectively in very diverse fields such as medicine, advertising, defense, education, or research for different purposes like training, learning or increasing user awareness on specific topics [8], [9], [10], [11], [12]. Traditionally, serious games have been formally evaluated using self-assessment questionnaires that attempt to measure the judgements and opinion of players, or pre-post assessment questionnaires that evaluate characteristics such as their knowledge before and after playing the game [13]. However, the use of learning analytics as a way of testing the effectiveness and design of serious games, as well as evaluating players, is now becoming more widespread, although these techniques are still usually combined with questionnaires [14]. Currently, learning analytics techniques are mainly applied to interaction data collected while the user is playing the video game. However, the data analyzed can come from different sources in what is called multimodal analytics, combining different forms of data collection to obtain richer evidence [15]. We consider that the use of bioelectrical signals can help to make a more objective assessment, using involuntary responses from users as evidence to complement their perceptions as collected by self-assessed questionnaires, or their interaction data.

This review analyzes the state of the art regarding the use of electric biosignals applied to video games, using them for both the validation of the effectiveness and applicability of the video game, and the evaluation of the impact and effects of the videogame on players. The review focuses on the use of EEG, ECG, EDA and EMG due to the ease of finding wearables and other commercial devices intended for application in real non-medical settings. Although eye-tracking is not a bioelectrical signal, we decided to include it in this review since an initial exploration showed that it is a relevant technique that is commonly used as a complement in studies that use biosignals with games, due to the widespread use of user-facing cameras and, to a lesser extent, virtual reality headsets. In this way we want to characterize the types of game where different sensors and signals are applied, how the corresponding experiments are carried out with users, and finally the role and interpretation of biosignals in each of these cases.

II. RELATED WORK

Video games are currently a very relevant field of research due to their widespread presence in society and their economic impact. Bioelectrical signals can be useful to better understand the effects of video games because they can contribute to obtain an evidence-based evaluation of the effects of videogames on players. For instance, in the field of serious games, biosignals may allow us to objectively evaluate video games as educational; or as therapeutic tools via their effects on players' health. As previously stated, we also include eye-tracking due to its co-occurrence in the research with bioelectrical signal use in games.

There are other reviews about biosignals and their use in videogames. The present review is not intended to study research in which biosignals are used as the main element of interaction. This kind of review can be found in [16], [17], covering the use of brain-generated signals as input controllers (BCI), as well as the devices and software used. [18] focuses on ''Affective Gaming'', and how the signals collected by different sensors can provide information to the player through the game and how the gaming experience can be changed by taking into account the emotional state of the player. Reference [19] reviews the use of the signal generated by the electrical activity of the skin (EDA) in different studies applied to learning and [20] review the use of electrocardiography (ECG) out of hospitals. Some others reviews like [21] are focused on providing overviews of techniques for biosignal processing. However, none of the previous reviews provides a vision from the point of view of video games, analyzing the possibilities of biosignals in research on video game design, their validation, or the evaluation of players for the specific case of serious games. One of the reasons for lack of reviews in this area may be that, when performing a video game validation and evaluating players, the most widely accepted methods are the use of external questionnaires, sometimes complemented by player interaction data analytics [13].

III. METHODOLOGY

The main objective of this review is to explore the use of bioelectrical signals in the field of video games to validate their design, or to evaluate and assess player characteristics while using the video game. To do so, we pose the following research questions:

- **RQ0.** What types of biosignals and sensors are most commonly used in videogames?
- **RQ1.** What variables or characteristics have been studied with each one of the biosignals?
- **RQ2.** In which game genres have biosignals been used to evaluate players, or to validate the games themselves?
- **RQ3.** How can biosensors be used to evaluate the effectiveness of a serious game?

RQ4. How many users are involved in each study as test subjects and what is the duration of the experiments?

In addition to answering these research questions, we also compile additional information to enrich the study and to better understand how games were developed or evaluated:

- Whether Learning Analytics or the collection of interaction data is being used to conduct the studies.
- What additional measuring instruments are used (surveys, logs, learning analytics…).

A. SEARCH STRATEGY

We follow the guidelines of Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) [22]. The search was performed querying 5 databases, including some of the main databases for education, psychology, computer science, health and general scientific research. The databases were: Association for Computing Machinery (ACM), SAGE, Science Direct (Elsevier), IEEE Xplore, and PubMed.

The search was carried out by concatenation of three sets of words addressing three aspects:

- Type of sensor/signal: which could be either "biosensors", "biosignals", "EEG", "Electroencephalography", "ECG", "electrocardiography", "EMG", "electromyography", "EDA", "electrodermal activity", "GSR, "galvanic skin response ", "SCR", "skin conductance response" OR "eye tracking", "heart rate"
- Purpose: represented by the terms "validation", "evaluation", "assessment".
- Field: "game" or "videogame" since we are interested in the use of the biosensors in the field of video games

In addition, we exclude those publications that contain Brain-computer interfaces (BCI) in the abstract since the study of the use of biosignals as a means of interaction with the video game is outside the scope of this paper. The final query was therefore:

- ("biosensors" OR "biosignals" OR "eeg" OR "ecg" OR "emg" OR "eda" OR "gsr" OR "scr" OR "eye tracking" OR "electroencephalography" OR "electrocardiography" OR "electromyography" OR "electrodermal activity" OR "galvanic skin response" OR "skin conductance response" OR "heart rate") AND ("evaluation" OR "validation" OR "assessment") AND ("game" OR "videogame") AND NOT "bci" AND NOT "brain-computer interfaces".

The search query was limited to publications from January 2015 to 2021 (both included) as we wanted to focus on the advances made in the last few years. The search was carried out in May 2021.

B. STUDY SELECTION

The inclusion criterion has been those studies that use any of the most common bioelectrical signals (complemented by eye tracking) as a tool to study the effect of the game on the player with the aim of validating the use of the video game or its mechanics and those studies that use biosignals together with the video game as a tool to evaluate the player.

On the other hand, we have excluded those studies that use biosignals as main input interfaces (BCI), or with the aim of providing feedback to the video game (biofeedback/affective gaming), or where the video game is used just as an interactive activity with the sole purpose of studying biosignals in a generic way or to create, train or validate artificial intelligence models not focused on video games.

The initial search and classification of the studies was carried out by a single researcher who applied the inclusion and exclusion criteria. This process was supervised by two collaborators who contrasted independently the criteria applied and validated whether the studies met the criteria.

After performing the queries, no further automation was used to include or exclude publications. The review of included studies was focused on extracting and annotating by keywords in a table the following variables: year, goal of the study; goal of the use of the target biosignal; the type of videogame and game platform; devices used to collect biosignal; methods of data collection during the study; number of users; details of the experiment; data anonymizatio; ethic; and study results highlights. In case of doubt or lack of information on the value of any of these variables, it was interpreted as unspecified data. In case of discrepancy of any variable evaluated in any publication, the document was reevaluated again until agreement was reached. For the results, the publications were grouped by keyword in each of the variables analyzed.

IV. RESULTS

A. PAPERS SELECTED USING INCLUSION CRITERIA

371 papers were obtained from the search, of which 81 met the inclusion criteria and were analyzed in depth. Figure 1 shows the process for the selecting the studies.

The number of publications appearing in the search according to the year of publication shows a continuous growing trend from 2015 to 2020, more than doubling in that period (see Figure 2).

B. TYPES OF BIOSIGNALS AND THEIR USE

Addressing RQ0, the most frequent signals among studies selected for inclusion are electrocardiograms (ECG), followed by electroencephalograms (EEG) and electrodermal activity (EDA) (Figure 3). The use of eye tracking devices to measure and follow players' gazes, and electromyograms (EMG) to detect the activation of muscles are also very common. These signals match some of the terms used in for the search. The use of devices to measure respiration, temperature, oxygen (both blood and inspired) and saliva have also appeared to a lesser extent.

In the following subsections, we present a summary of the use of the main signals and measurement devices, addressing RQ1.

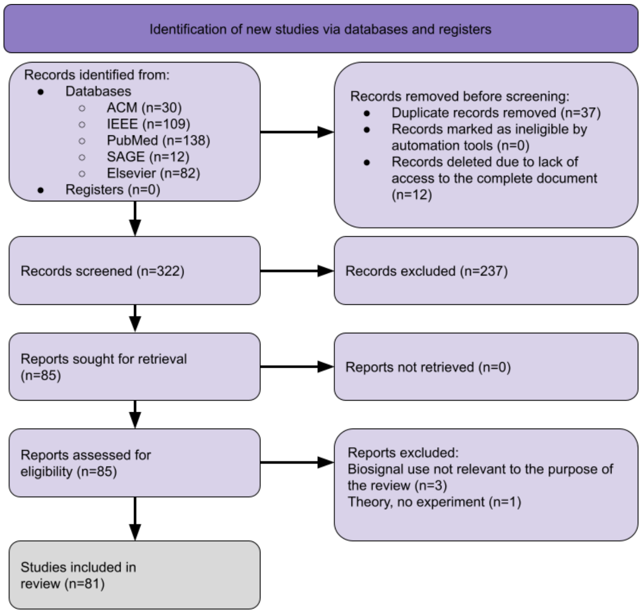

FIGURE 1. Search and selection process flow diagram.

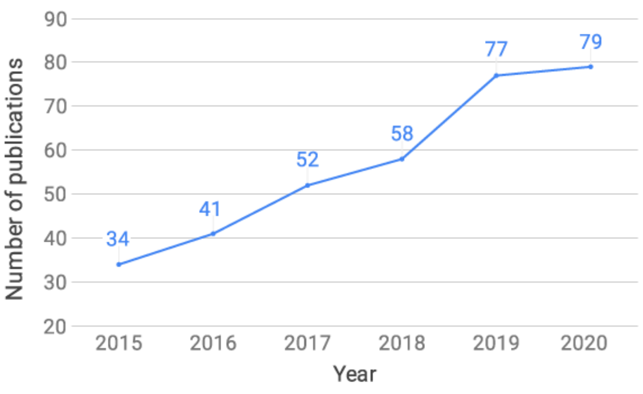

FIGURE 2. Number of publications related to biosignals and video games over the last 6 years. Steady growth can be observed.

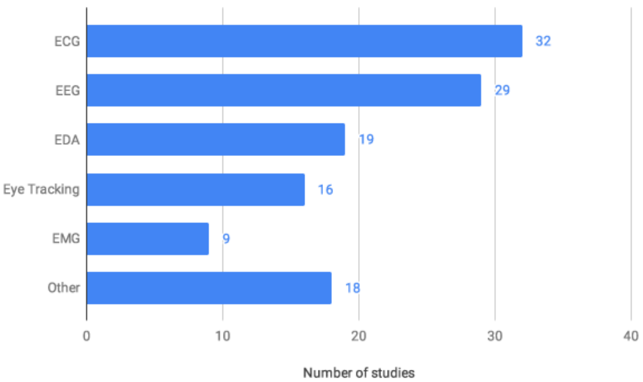

FIGURE 3. Number the studies for each kind of biosignal.

1) ELECTROCARDIOGRAM

Electrocardiograms (ECG) measure different aspects such as heart rate, pulse variability and pulse rate. This signal is used in various studies as a proxy to determine different physical and mental states of the player: emotional valence, mental effort, task difficulty, frustration, immersion and physical stress (see Table 1).

TABLE 1. Use of electrocardiogram.

Signal objective	Studies reference	# Studies
Physical Stress / Workload	[23]–[33]	11
Emotional Valence	[34]–[38]	5
Signal Comparison	[39]–[42]	4
Mental Effort	[43], [44]	2
Stress	[45], [46]	2
Arousal	[47], [48]	2
Frustration / Boredom	[49]	1
Game Experience	[50]	1
Immersion	[51]	1
Motion Sickness	[52]	1
Task Difficulty	[53]	1
Cognitive Performance	[54]	1

2) ELECTRODERMAL ACTIVITY

Electrodermal activity (EDA) measures the variation of the electrical characteristics of the skin caused by sweat gland activity. This signal is used to identify different aspects about the player such as arousal, stress, interest, cognitive performance, anxiety, and engagement (see Table 2).

3) ELECTROENCEPHALOGRAM

An electroencephalogram (EEG) measures the electrical activity of the brain. The electrical signals of the brain are mainly used in studies to identify cognitive states in the player such as boredom or frustration (cognitive load), enjoyment, attention, emotional valence (positivity or negativity of an emotion) and level of immersion of the players (see Table 3). This brain activity is measured using different waves according to their frequency [61]:

- Delta waves (0.2-4 Hz), predominant during sleep.
- Theta waves (4-8 Hz), predominant when internal information is being processed and the individual is disconnected from the outside world, self-absorbed. They are also present during deep meditation.
- Alpha waves (8-12 Hz), predominant when the Central Nervous System is at rest, relaxed but awake and attentive. It is also a frequency that the brain uses as a reward after a job well done.

TABLE 2. Use of electrodermal activity.

Signal objective	Studies reference	# Studies
Arousal	[34]–[38], [43], [44], [48], [55]	9
Stress	[45], [46], [49], [56], [57]	5
Immersion	[51], [58]	2
Cognitive Performance	[54]	1
Anxiety	[59]	1
Interest	[60]	1
Arousal	[34]–[38], [43], [44], [48], [55]	9
Stress	[45], [46], [49], [56], [57]	5
Immersion	[51], [58]	2
Cognitive Performance	[54]	1
Anxiety	[59]	1
Interest	[60]	1

- Beta waves (12-30 Hz), appearing in states where attention is directed to external cognitive tasks, when attentive and involved in solving everyday tasks or problems, also during decision making or when concentrated.
- Gamma waves (30-90 Hz), observed in bursts when the brain is in a state of high resolution.

4) ELECTROENCEPHALOGRAM

Electromyograms (EMG) measure the electrical activity of muscles and nerves. Their use can greatly vary depending on the muscles it is placed on. For example, when used on the face, the emotional valence of the player can be checked, whereas, when used on extremities, EMGs can measure the level of activation of local muscles to detect damage or determine levels of effort (see Table 4).

5) EYE TRACKING

Tracking of the player's gaze reveals the regions of the screen that they look at, and therefore which game elements attract more attention; and also the extent to which the player's gaze is stable. It allows for the evaluation of the game interface, the time that players spend looking at each element, and can even detect possible cognitive problems in players (see Table 5).

C. TYPE OF PUBLICATION ACCORDING TO THE PURPOSE OF THE BIOSIGNALS

Six types of publications have been identified according to the purpose and the analysis of the biosignals used (n = # denotes the number of studies found):

- Studies focused on user experience, identifying whether the player is entertained while playing and whether the level of difficulty is appropriate for their skills. (User Experience, n = 26).
- Studies that explore the biosignals received and compare their characteristics in different groups of users while using video games. These publications have more of an exploratory approach to the use of the signals and their interpretation. Unlike the rest, they do not seek to evaluate a characteristic of the player (e.g., emotional valence, arousal) or the video game (engagement, efficacy) by means of the biosignals. And they usually use several groups (intervention and control) to compare the characteristics of the signals between groups (Exploratory, n = 19).

TABLE 3. Use of electroencephalogram.

Signal objective	Studies reference	# Studies
Signal Comparison*	[62]–[68]	7
Frustration / Boredom / Cognitive Load	[43], [44], [69]–[72]	6
Arousal	[73]–[76]	4
Emotional Valence	[73]–[76]	4
Attention / Meditation	[77]–[79]	3
Enjoyment	[76], [80]	2
Game Experience	[81]	1
Stress	[82]	1
Cognitive Performance	[83]	1
Difficulty in decision-making	[84]	1
Patterns neural activity	[85]	1
Academic Skills	[86]	1
Activation Level	[87]	1
Immersion	[58]	1

** Signal Comparison: Comparing EEG waves between users, game moments or questionnaire responses without attributing a specific meaning to the signal.*

TABLE 4. Use of electromyogram.

Signal objective	Studies reference	# Studies
Emotional Valence	[36], [43], [44], [49]	4
Physical Stress	[88], [89]	2
Activation Level	[90], [91]	2
Button Press	[84]	1

TABLE 5. Use of eye tracking.

Signal objective	Studies reference	# Studies
Gaze track	[92]–[101]	10
Gaze Stability	[102]	1
Cognitive Load	[53]	1
Cognitive Performance	[103]	1
Arousal	[73]	1
Emotional Valence	[73]	1
Difficulty in decision-making	[84]	1

- Studies focused on exploring the effects of a commercial video game and its benefits or drawbacks. (Game Evaluation, n = 13).
- Studies focused on testing and verifying the effects of a serious game on its target (Game Validation, n = 10).
- Studies focused on using video games as an evaluation tool to measure a player characteristic according to their performance and interactions with a video game. The measured characteristic can be the severity of a disease, an injury or the knowledge of a player (User assessment, n = 9).
- Studies focused on analyzing player interactions according to the layout of the graphical interface of the game or the features and screen configuration used (Game Interface, n = 4).

D. SENSORS AND DEVICES

All these signals are measured by different devices. In the publications reviewed, we found a wide variety of devices and providers. Some of the companies are specialized in one type of device to be sold to other companies, such as Tobii, Polar, Emotiv and Empatica. It is also noteworthy the use of medical machines and devices (mainly for the medical sector) by companies such as Compumedics and Nihon Kohden. To a lesser extent, there are studies that use and adapt their own devices created with small sensors and low-cost solutions, examples are the devices of Bitalino and Open BCI (Brain Computer Interface). These last two low-cost solutions provide free software to perform visualization and analysis of the signals, as opposed to the rest of the solutions where software is generally private and is used by means of a license fee. In addition, in the case of studies focused on games where physical activity is performed, it is common to find devices adapted to exercise and special controllers to interact with the game, such as bicycles adapted to the activity performed with specific sensors. Table 6 summarizes companies and devices that appear in the reviewed studies.

TABLE 6. Use of electrocardiogram.

Company	URL (prefix with https://)	Specific biodevices and biosignals that appears in reviewed studies
Biopac	www.biopac.com/	BIOPAC EL507 (EDA) Biopac MP150 + EL 500 Series (EDA, EMG, EEG, ECG) BN-PPGED (EDA)
Microsoft	No info	Microsoft Band 2 (ECG)
Tobii	www.tobii.com/	Tobii 2.0 (Eye Tracking) Tobii Pro 2 (Eye Tracking) Tobii T120" (Eye Tracking)
Bitalino	bitalino.com/	No specific device (EDA, ECG, EMG)
Merlin-Digital	merlin-digital.com/	Merlin-digital Heart Rate Monitor PRO (ECG)
SensoMotoric Instruments	No info	RED250 (Eye Tracking) RED-m (Eye Tracking)
Electrical Geodesics, Inc.	www.egi.com/	No specific device (EEG)
EMOTIV	www.emotiv.com/	EMOTIV EPOC-X (EEG)
NeuroSky	neurosky.com/	MindWave (EEG)
Muse	choosemuse.com/	Brain EE Muse Headband (EEG)
WildDivine (Unyte)	wilddivine.com/	No specific device (EEG)
Compumedics	compumedicsneuroscan .com/	No specific device (EEG)
Philips	www.centralamerica .philips.com/healthcare/ medical-specialties/ cardiology	IntelliVue MP50 (ECG)
Union Tool Co.	www.uniontool.co.jp/en/	WHS-1 (ECG)
g.tec medical engineering	www.gtec.at/	No specific device (ECG), (EDA) g.USBamp (EEG)
Technonext Co. Ltd.	No info	No specific device (Temperature)
Croswell Co.	No info	No specific device (ECG)
Empatica	www.empatica.com/en-eu/	E4 wristband (EDA, ECG)
OpenBCI	openbci.com/	No specific device (EEG)

TABLE 6. *(Continued.)* Use of electrocardiogram.

JINS	www.jins.com/us/	JINS eyewear (Eye Tracking)
SR Research	www.sr-research.com/	EyeLink 1000 Plus (Eye Tracking)
ANT Neuro	www.ant-neuro.com/	No specific device (EEG)
Biocom Technologies	www.biocomtech.com/	HRM-02 (Photoplethysmography)
SensorMedics	No info	Encore229 Vmax (Oxygen)
Polar	www.polar.com	No specific device (ECG)
MedGraphics	medgraphics.co.uk/	No specific device (Oxygen)
Delsys	delsys.com/	Trigno (EMG)
COSMED	www.cosmed.com/en/	K4b2 (Oxygen)
MindWare Technologies	mindwaretech.com/	No specific device (Oxygen)
VU-AMS	http://www.vu-ams.nl/	No specific device (ECG, EDA)
BioSemi	www.biosemi.com/	ActiveTwo system (EEG)
Nihon Kohden	us.nihonkohden.com/	No specific device (EEG)
Advanced Brain monitoring	advancedbrainmonitoring.com/	ABM X-10 (EEG)
Shimmer	www.shimmersensing.com	Shimmer3 GSR (EDA)
Siemens	www.siemens-healthineers.com/	3 T MRI scanner (MRI)
Omron	www.professional.omron-healthcare.es/en	OMRON HEM-7113 (Blood Pressure)
ActiGraph	actigraphcorp.com/	GTX3 (ECG)

E. TYPE OF VIDEOGAMES AND GENRE

Most of the studies found use already developed and commercial off-the-self (COTS) video games. These commercial video games can also be ''Free2Play'', games that are free to play but that may include some premium features that require a payment. To a lesser extent, we also found a significant number of studies that use serious games (mostly related to the health field). Finally, there is a minority of studies that use adaptations of other video games (by modifying or adding new game mechanics), or that create their own video games their research purposes (DreamsKeeper, KittenQuest, Tilt-Ball Game). There are also studies using free, open-source video games focused on leisure but without a commercial approach (e.g., Open Source Asteroids, Super Tux Kart, Wizznic). Figure 4 shows the number of studies using games of each of these types.

Most games are played by the user on computers, mobile devices and consoles. Some of them make use of virtual reality (11). There are a few studies focused on ''exergames'' that use special hardware, which can be composed for example of special sport or bicycle tapes. Some exergames studies also use the Kinect or the Wii Fit devices (Figure 5).

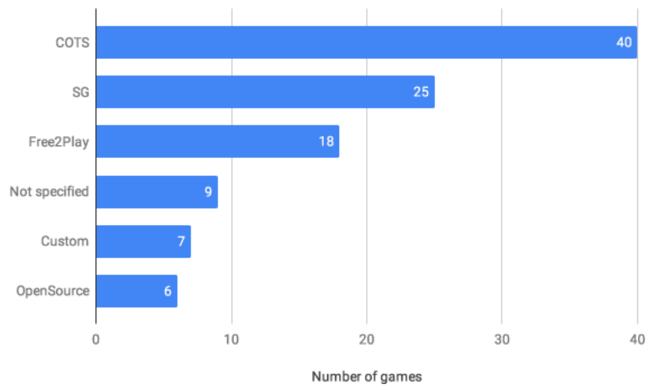

FIGURE 4. Types of games that appear in publications according to their purpose and cost.

Addressing RQ2, among the game genres most used by the different studies analyzed are shooters, puzzle games, infinite runner games, action and skill games, simulation games, and exergames. Most of the games used belong to highly interactive game genres (blue), with very short feedback cycles where the player must react quickly (Figure 6).

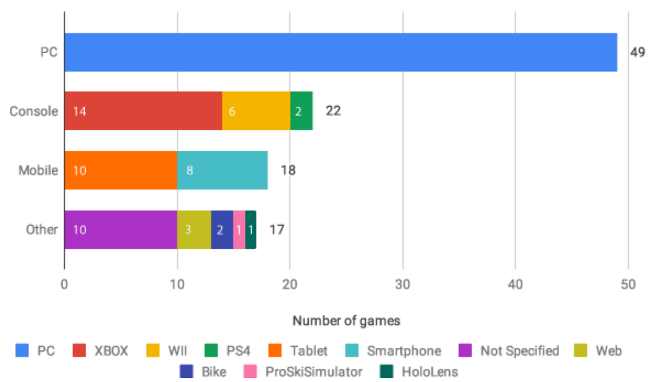

FIGURE 5. Number of videogames per platform.

F. TYPE OF VIDEOGAMES AND GENRE

Questionnaire data is then compared with the biosignals obtained to help in their interpretation and in the validation of the biosignal method. However, this fact may also be related to the circumstance that most of the videogames used in the experiments are COTS and they normally either do not collect interaction analytics, or if collected, it is not available to the researchers.

There is also a widespread use of experiment recording (player's face and game screen) to identify and relate significant events to important peaks and patterns in the collected biosignals.

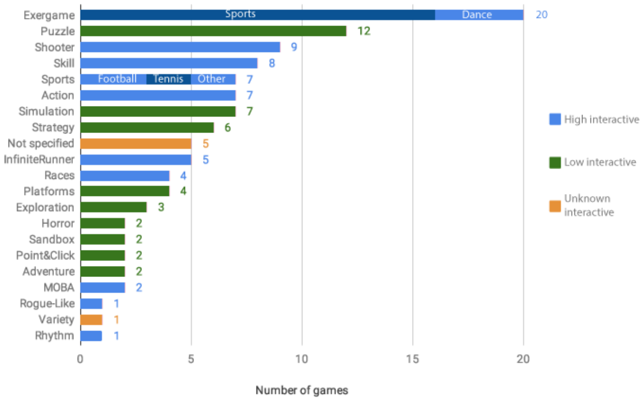

FIGURE 6. **Genre of the videogames that appears in the publications.**

G. OTHER ADDITIONAL DATA RESOURCES

Most of the studies and experiments continue to complement and contrast the biosignal information with user data obtained from user questionnaires, instead of only using information on how players played during the game (game interaction analytics). Those questionnaires are used not only to capture demographic or psychology data about players, but also to perform measurements with validated and standardized methods widely accepted in the domain. Questionnaire data is then compared with the biosignals obtained to help in their interpretation and in the validation of the biosignal method. However, this fact may also be related to the circumstance that most of the videogames used in the experiments are COTS and they normally either do not collect interaction analytics, or if collected, it is not available to the researchers.

There is also a widespread use of experiment recording (player's face and game screen) to identify and relate significant events to important peaks and patterns in the collected biosignals.

H. SAMPLE SIZE AND EXPERIMENT TIME

Due to the complexity of configuring and calibrating biosignal measurement devices, the total experimentation time is very long, even though the biosignal data collection times are surprisingly short, rarely exceeding the 10-minute mark. The use of these devices often requires data collection both at rest (to provide a baseline) and during normal player activity. In those studies where the playing time is longer, the collection and analysis of the signal is performed during short periods of time, usually before, in the middle and at the end of the video game activity. In general, the studies give very few details about the volume of data captured and even how such data is formatted or processed.

On the other hand, addressing RQ4, the number of users who tend to participate is also lower than what is usually seen in other video game studies. Of the 85 experiments reported in the 81 studies, a majority (77 studies) were conducted with fewer than 75 users, and even with less than 50 participants (69 studies). A single study had 300 users, and only 3 in total had over 200 users (see Figure 7).

The studies with the largest number of users are characterized either by being conducted over long periods of time (+6 weeks) or by having very short play times. In general, studies with large samples collect only one biosignal (i.e., EEG, ECG or use eye tracking).

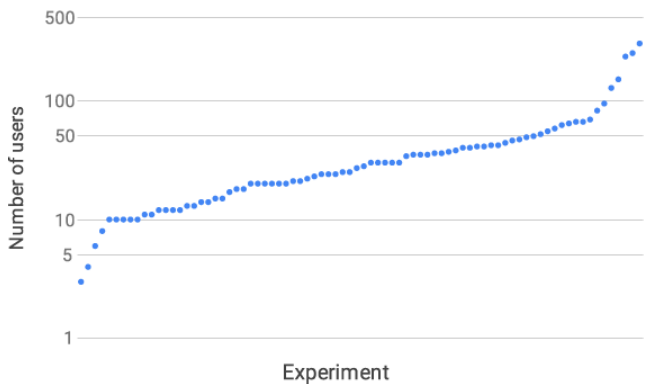

FIGURE 7. **Number of users per experiment (note log scale on y-axis).**

I. SIGNAL PROCESSING AND DATA ANALYSIS

When analyzing the signals, the studies analyzed in general do not show details about the process performed beyond mentioning that the signal is filtered; in many cases this is due to the use of third-party software or the devices themselves send numerical data with which the researchers work, for example HR values in ECG, conductance values in EDA or fixations number in Eye Tracker. 38 of the studies (46.9%) mention the software used to process the signals. Among the software used we find names such as: AcqKnowledge 4.3 software, Brain Vision Analyzer, BrainStream, Emotiv tm software, BCI2000, EEGLAB toolbox, g.Recorder and EyeLink Data Viewer, SigmaPlot Software, EMGworks, CURRY Neuroimaging Suite, Biograph Infiniti, Automatic Artifact Removal, sLORETA, VU-DAMS software, Xavier TechBench Software, OpenViBE, iMotions and SMI Experiment Center. The software used is very varied and rarely repeated. On the other hand, only 14 studies (17.3%) mention the algorithms used or give details of the process followed and in general not much detail is given either. Some of the algorithms include the Butterworth filter, Low-Filter or Chebyshev band pass filter, various signal transformation methods such as Fourier Transform or Daubechies wavelets, and peak detection algorithms.

Once collected and processed, data must be compared. 70 of the analyzed studies (86.4%) use statistical analysis to compare data collected from various sources or to compare data at different instants in time. 12 of the studies (14.8%) use Machine Learning as an analysis method [36], [45], [50],

[53], [54], [73], [74], [75], [80], [82], [83], [97]. 6 of the analyzed studies (7.5%) simply show the distribution and values of the collected data or relate the collected signal data to events that occurred during the game [25], [49], [52], [57], [81], [101].

J. ETHICS

Due to the collection of data and signals from human subjects, most of the studies explicitly state that they required informed consent from players and/or previous approval from an ethics committee. However, these studies do not mention how they store and protect the personal and gaming data of their participants (e.g., if personal data is stored encrypted). That is, they do not explicitly state their compliance with data protection regulations of different countries (e.g., GDPR in the EU). This is an important aspect both ethically and legally, especially in countries with more restrictive regulations, such as members of the European Union.

V. DISCUSSION

When it comes to signal collection, the number of signals and devices is very varied. Also, different user characteristics were measured with different techniques, using EEG, ECG, EDA or EMG depending on the study. These signals are used alone or combined as a proxy to assess a wide variety of game and player characteristics across different studies. And it is not clear from these studies which technique or biosignal is better: for example, workload and stress on the player can be measured by ECG and EEG. Immersion is also measured by different studies in different ways, mainly using ECG, EEG or EDA. Difficulty in decision making during gaming sessions has been measured with both Eye Tracker and EEG. Player arousal and emotional valence can be measured by combining ECG and EDA, but also by using EEG.

This highlights the lack of standards for biosignal use as applied to gaming. There is no widely accepted consensus on the most effective method to measure the different characteristics of users. There is therefore a need for more studies comparing different biosensors and signals for player or video game assessments. Among the studies analyzed, the most used signals are ECG and EEG. EMG, on the other hand, is the least used – and most of the studies that make use of it are those that use games focused on physical exercise (exergames).

The use of biosignals seems to be an ideal method for evidence-based assessment, studying how players learn, better evaluate non-conscious effects on players, measure user engagement and evaluate the level of difficulty of serious games. The use of video games in combination with biosignals has proven to be useful tools for the detection and evaluation of diseases, as in the case of [92], where they have been applied to players with Alzheimer's disease. Use of biosignals is useful in the analysis of the design of any video game since it allows to study the effect of its difficulty (or lack of it) on the players [70], [84] and to help to understand the way in which players make decisions during the game session [94]. It also allows designers to better understand the flow of the game and to study how multiplayer gameplay affects the cognition and perception of the game itself by its players [69]. These techniques could be applied to study video games on negotiation skills training and collaborative games. Biosignals also allow the study of the effect of virtual reality on players as well as the comparison between highly immersive and non-immersive environments [48], [83]. Moreover, biosignals are applicable in the comparison of tasks performed during the use of a video game and those performed in real life. Of particular interest is the difference in attention that occurs in the user [77], which can be used to study the advantages in the use of games as tools that go beyond pure entertainment. It should also be noted that biosignals can also allow the evaluation of users with mobility problems or mental disabilities and issues as in the case of [103] and [59] respectively. This is especially valuable for users who, due to their characteristics, may be difficult to evaluate in an objective way with traditional methods such as self-reporting questionnaires.

Also, it is notable that most of the studies focus on the use of biosignals with commercial video games and physical activity games (exergames). Among included studies, there is a predominance of highly interactive, action-oriented video games (sports, exergames, shooters . . .); and comparatively, only a small number of conversational video games and graphic adventures. This could indicate that more reflexive, lower-paced video games are more difficult to analyze based on variations in the collected biosignals; or that there are more effective methods based on learning analytics and stealth assessment for these game genres.

Among studies using serious games, most of these belong to the field of health, with a very limited representation in the field of education. With the growth of the field of study of serious games and the great variety available, it is surprising that their representation in this review is so limited (23.8%). Scarcity of such studies about educational SGs may be due to several factors: (1) difficulty in finding volunteers from educational institutions to conduct experiments of this type with serious games. In some cases, studies such as [46], [53], [58], and [100] decide to provide financial compensation to participants. However, this is not always an option. Also, in many cases, it is necessary to work with minors, imposing extra requirements to ensure that studies are ethically sound. (2) The duration of the serious games, generally long and designed to span several sessions, together with the difficulty of biosensor usage and calibration. The use of heavy and voluminous devices also can affect player experience by making players feel uncomfortable over time. (3) Problems in the detection and interpretation of learning-related signals due to the complexity of cognitive processes. The use, processing and study of biosignals is a complex field of research that requires technical expertise and/or licensing fees for specialized software in addition to the sensors. This can complicate the use of the devices in other research fields such as education if cooperation between research groups and companies does not take place. (4) Finally, the high price of these devices should not be underestimated, although there are low-cost sensor companies that, together with machine learning techniques for the generalization of analysis and interpretation of results, can facilitate their application [73]. Furthermore, there does not seem to be a standard in the data format of the signals sent by the different devices of the different companies. This hinders the interoperability and systematization of platforms dedicated to signal analysis in a way that can be compatible with different sensors without prior data processing.

Conducting experiments deploying games with actual users in real domains has always been difficult, but this difficulty is increased by the complexity of biodevices and those related to handling the collected data. Biodevices frequently require calibration, and presence of noise and interference in signals is common, resulting in samples being invalidated. Biosignals are still very complex to apply in large deployments; indeed, half of the studies in this review were conducted with less than 30 users. Although it is not always explicitly stated, from descriptions of experimental settings we infer that the number of users from whom parallel samples were collected is most often around 6 or less participants. This means that experiments are often extended for weeks in order to collect larger sample sizes. In addition, highly-controlled rooms and environments are used. Additionally, even when studies address the ethical issues that may arise when conducting experiments on humans and collecting their data, the correct treatment of that data is still an issue long after it is collected. Studies should describe how user data was stored and secured, and the measures taken to ensure the ethical exploitation of that data.

A. FUTURE WORK

Although there are still limitations in the application of biosignals in combination with video games in realistic scenarios and in with large numbers of users, we believe that their use will be increasingly common in studies of video games where users are to be evaluated. This is especially important serious games, both to evaluate users and to validate the video games themselves. Future growth will be motivated by the growing interest of companies in the usage of Virtual Reality systems, haptic systems and brain computer interfaces for both recreation and serious purposes; and in the creation of game-based metaverses. We think that this trend will result in the creation of more affordable and reliable biosensor devices for the massive gaming market. It would also be desirable to have more open software environments such as OpenBCI, which can simplify the analysis of biosignals while reducing dependence on hardware vendors, thus allowing a more widespread and cost-effective analysis of biosignals.

B. LIMITATIONS

The current review has several limitations. First, as all systematic reviews, it is limited by the search terms used, the databases included, and the temporal window during which the actual searches for papers were carried out. The search was mainly limited to the use of EDA, ECG, Eye Tracking, EEG and EMG signals, since we consider that these signals, due to their characteristics and the devices with which they are collected, are the most applicable to video games. However, these are not the only signals that can be applied, and in fact studies have appeared in which other signals have been used (e.g., blood oxygen or saliva). However, as of this writing, these alternate signals are considerably less popular than those examined in this review.

REFERENCES

[1] Y. N. Singh, S. K. Singh, and A. K. Ray, "Bioelectrical signals as emerging biometrics: Issues and challenges," *ISRN Signal Process.*, vol. 2012, pp. 1–13, Jul. 2012.

[2] M. Antoniak, "Benefits and threats of neuromarketing: Theoretical background and practical use," *Sci. Papers Silesian Univ. Technol. Org. Manage.*, vol. 2020, no. 148, pp. 9–25, 2020.

[3] M. Piwowarski, *Neuromarketing Tools in Studies on Models of Social Issue Advertising Impact on Recipients*. Berlin, Germany: Springer, 2018.

[4] K. C. Ewing, S. H. Fairclough, and K. Gilleade, "Evaluation of an adaptive game that uses EEG measures validated during the design process as inputs to a biocybernetic loop," *Frontiers Human Neurosci.*, vol. 10, pp. 1–13, May 2016.

[5] G. J. Nalepa, B. Giżycka, K. Kutt, and J. K. Argasiński, "Affective design patterns in computer games. Scrollrunner case study," in *Proc. FedCSIS Commun. Papers*, vol. 13, 2017, pp. 345–352.

[6] A. Kawala-Janik, M. Podpora, A. Gardecki, W. Czuczwara, J. Baranowski, and W. Bauer, "Game controller based on biomedical signals," in *Proc. 20th Int. Conf. Methods Models Automat. Robot. (MMAR)*, 2015, pp. 934–939.

[7] D. R. Michael and S. L. Chen, *Serious Games: Games That Educate, Train, and Inform*. Muska & Lipman/Premier-Trade, Oct. 2005.

[8] A. Calvo-Morata, C. Alonso-Fernández, M. Freire, I. Martínez-Ortiz, and B. Fernández-Manjón, "Creating awareness on bullying and cyberbullying among young people: Validating the effectiveness and design of the serious game conectado," *Telematics Informat.*, vol. 60, Jul. 2021, Art. no. 101568.

[9] T. M. Connolly, E. A. Boyle, E. MacArthur, T. Hainey, and J. M. Boyle, "A systematic literature review of empirical evidence on computer games and serious games," *Comput. Educ.*, vol. 59, no. 2, pp. 661–686, Sep. 2012.

[10] M. M. Yamin, B. Katt, and M. Nowostawski, "Serious games as a tool to model attack and defense scenarios for cyber-security exercises," *Comput. Secur.*, vol. 110, Nov. 2021, Art. no. 102450.

[11] M. Muratet, P. Torguet, J.-P. Jessel, and F. Viallet, "Towards a serious game to help students learn computer programming," *Int. J. Comput. Games Technol.*, vol. 2009, pp. 1–12, May 2009.

[12] M. Cagatay, P. Ege, G. Tokdemir, and N. E. Cagiltay, "A serious game for speech disorder children therapy," in *Proc. 7th Int. Symp. Health Informat. Bioinf.*, Apr. 2012, pp. 18–23.

[13] A. Calderón and M. Ruiz, "A systematic literature review on serious games evaluation: An application to software project management," *Comput. Educ.*, vol. 87, pp. 396–422, Sep. 2015.

[14] C. Alonso-Fernández, A. Calvo-Morata, M. Freire, I. Martínez-Ortiz, and B. Fernández-Manjón, "Applications of data science to game learning analytics data: A systematic literature review," *Comput. Educ.*, vol. 141, Nov. 2019, Art. no. 103612.

[15] P. Blikstein and M. Worsley, "Multimodal learning analytics and education data mining: Using computational technologies to measure complex learning tasks," *J. Learn. Anal.*, vol. 3, no. 2, pp. 220–238, 2016.

[16] R. A. Ramadan and A. V. Vasilakos, "Brain computer interface: Control signals review," *Neurocomputing*, vol. 223, pp. 26–44, Feb. 2017.

[17] B. Kerous, F. Skola, and F. Liarokapis, "EEG-based BCI and video games: A progress report," *Virtual Reality*, vol. 22, no. 2, pp. 119–135, Jun. 2018.

[18] R. Robinson, K. Wiley, A. Rezaeivahdati, M. Klarkowski, and R. L. Mandryk, "'Let's get physiological, physiological!': A systematic review of affective gaming," in *Proc. Annu. Symp. Comput.-Hum. Interact. Play*, Nov. 2020, pp. 132–147.

[19] A. Horvers, N. Tombeng, T. Bosse, A. W. Lazonder, and I. Molenaar, ''Detecting emotions through electrodermal activity in learning contexts: A systematic review,'' *Sensors*, vol. 21, no. 23, p. 7869, 2021.

[20] A. Bansal and R. Joshi, ''Portable out-of-hospital electrocardiography: A review of current technologies,'' *J. Arrhythmia*, vol. 34, no. 2, pp. 129–138, 2018.

[21] E. M. Tamil, N. S. Bashar, M. Y. I. Idris, and A. M. Tamil, ''A review on feature extraction & classification techniques for biosignal processing (Part III: Electromyogram),'' in *Proc. 4th Kuala Lumpur Int. Conf. Biomed. Eng.*, vol. 21, no. 1, 2008, pp. 117–121.

[22] M. J. Page et al., ''The PRISMA 2020 statement: An updated guideline for reporting systematic reviews,'' *Systematic Rev.*, vol. 10, no. 1, p. 89, Dec. 2021.

[23] C. McGregor, B. Bonnis, B. Stanfield, and M. Stanfield, ''Integrating big data analytics, virtual reality, and ARAIG to support resilience assessment and development in tactical training,'' in *Proc. IEEE 5th Int. Conf. Serious Games Appl. Health (SeGAH)*, Apr. 2017, pp. 1–7.

[24] J. C. Silva De Sousa, C. Torriani-Pasin, A. B. Tosi, R. Y. Fecchio, L. A. R. Costa, and C. L. D. M. Forjaz, ''Aerobic stimulus induced by virtual reality games in stroke survivors,'' *Arch. Phys. Med. Rehabil.*, vol. 99, no. 5, pp. 927–933, May 2018.

[25] B. C. Bock, H. Thind, S. I. Dunsiger, E. R. Serber, J. T. Ciccolo, V. Cobb, K. Palmer, S. Abernathy, and B. H. Marcus, ''Exercise videogames for physical activity and fitness: Design and rationale of the Wii heart fitness trial,'' *Contemp. Clin. Trials*, vol. 42, pp. 204–212, May 2015.

[26] M. Khoury, D. B. Phillips, P. W. Wood, W. R. Mott, M. K. Stickland, P. Boulanger, G. R. Rempel, J. Conway, A. S. Mackie, and N. S. Khoo, ''Cardiac rehabilitation in the paediatric Fontan population: Development of a home-based high-intensity interval training programme,'' *Cardiol. Young*, vol. 30, no. 10, pp. 1409–1416, Oct. 2020.

[27] N. E. Campos, J. P. Heinzmann-Filho, N. A. Becker, D. Schiwe, M. F. Gheller, I. S. de Almeida, and M. V. F. Donadio, ''Evaluation of the exercise intensity generated by active video gaming in patients with cystic fibrosis and healthy individuals,'' *J. Cystic Fibrosis*, vol. 19, no. 3, pp. 434–441, May 2020.

[28] P. Soltani, P. Figueiredo, J. Ribeiro, R. J. Fernandes, and J. P. Vilas-Boas, ''Physiological demands of a swimming-based video game: Influence of gender, swimming background, and exergame experience,'' *Sci. Rep.*, vol. 7, no. 1, pp. 1–7, Dec. 2017.

[29] T. McBain, M. Weston, P. Crawshaw, C. Haighton, and I. Spears, ''Development of an exergame to deliver a sustained dose of high-intensity training: Formative pilot randomized trial,'' *J. Med. Internet Res.*, vol. 20, no. 3, 2018.

[30] L. M. M. Sampaio, S. Subramaniam, R. Arena, and T. Bhatt, ''Does virtual reality-based Kinect dance training paradigm improve autonomic nervous system modulation in individuals with chronic stroke?'' *J. Vascular Interventional Neurol.*, vol. 9, no. 2, pp. 21–29, 2016.

[31] C. Höchsmann, N. Zürcher, A. Stamm, and A. Schmidt-Trucksäss, ''Cardiorespiratory exertion while playing video game exercises in elderly individuals with type 2 diabetes,'' *Clin. J. Sport Med.*, vol. 26, no. 4, pp. 326–331, 2016.

[32] I. C. A. A. Soares, J. S. A. da Silva Cabral, M. I. Knackfuss, I. A. T. Fonseca, G. A. Cardoso, and A. V. da Costa, ''Reality and virtual: Hemodynamic variables and rating of perceived exertion between dance sessions and active videogame just dance in women,'' *Games Health J.*, vol. 10, no. 3, pp. 174–179, Jun. 2021.

[33] J. L. D. Brito-Gomes, R. J. Perrier-Melo, A. F. de Brito, and M. C. da Costa, ''Videogames ativos promovem beneficios cardiovasculares em adultos jovens? Ensaio clínico randomizado,'' *Rev. Bras. Ciencias do Esporte*, vol. 40, no. 1, pp. 62–69, 2018.

[34] M. Morando, S. Ponte, E. Ferrara, and S. Dellepiane, ''Biophysical and motion features extraction for an effective home-based rehabilitation,'' in *Proc. Int. Conf. Bioinf. Res. Appl. (ICBRA)*, 2017, pp. 79–85.

[35] F. W. Petersen, L. E. Thomsen, P. Mirza-Babaei, and A. Drachen, ''Evaluating the onboarding phase of free-to-play mobile games: A mixed-method approach,'' in *Proc. Annu. Symp. Comput.-Hum. Interact. Play*, Oct. 2017, pp. 377–388.

[36] W. Yang, M. Rifqi, C. Marsala, and A. Pinna, ''Physiological-based emotion detection and recognition in a video game context,'' in emphProc. Int. Joint Conf. Neural Netw., Jul. 2018, pp. 1–8.

[37] M. J. van Bennekom, P. P. de Koning, M. J. Gevonden, M. S. Kasanmoentalib, and D. Denys, ''A virtual reality game to assess OCD symptoms,'' *Frontiers Psychiatry*, vol. 11, pp. 1–9, Jan. 2021.

[38] S. Kirginas, A. Psaltis, D. Gouscos, and C. Mourlas, ''Studying children's experience during free-form and formally structured gameplay,'' *Int. J. Child-Comput. Interact.*, vol. 28, Jun. 2021, Art. no. 100248.

[39] A. Suganuma, S. Ohara, H. Inoue, and N. Tetsutani, ''Feature classification of heart rate variability depending on difficulty levels of a puzzle game,'' in *Proc. Int. Work. Adv. Image Technol. (IWAIT)*, 2018, pp. 1–4.

[40] C. V. Russoniello, M. T. Fish, and K. O'Brien, ''The efficacy of playing videogames compared with antidepressants in reducing treatment-resistant symptoms of depression,'' *Games Health J.*, vol. 8, no. 5, pp. 332–338, Oct. 2019.

[41] D. Lee, J. Park, K. Namkoong, S. J. Hong, I. Y. Kim, and Y.-C. Jung, ''Diminished cognitive control in Internet gaming disorder: A multimodal approach with magnetic resonance imaging and real-time heart rate variability,'' *Prog. Neuro-Psychopharmacol. Biol. Psychiatry*, vol. 111, Dec. 2021, Art. no. 110127.

[42] M. Behnke, M. Kosakowski, and L. D. Kaczmarek, ''Social challenge and threat predict performance and cardiovascular responses during competitive video gaming,'' *Psychol. Sport Exerc.*, vol. 46, Jan. 2020, Art. no. 101584.

[43] Y. Bian, C. Yang, F. Gao, H. Li, X. Sun, X. Meng, and Y. Wang, ''A physiological evaluation model for flow-experience in VR games: Construction and preliminary test,'' in *Proc. Int. Conf. Identificat., Inf., Knowl. Internet Things (IIKI)*, Oct. 2015, pp. 244–249.

[44] Y. Bian, C. Yang, F. Gao, H. Li, S. Zhou, H. Li, X. Sun, and X. Meng, ''A framework for physiological indicators of flow in VR games: Construction and preliminary evaluation,'' *Pers. Ubiquitous Comput.*, vol. 20, no. 5, pp. 821–832, Oct. 2016.

[45] S. Ishaque, A. Rueda, B. Nguyen, N. Khan, and S. Krishnan, ''Physiological signal analysis and classification of stress from virtual reality video game,'' in *Proc. 42nd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2020, pp. 867–870.

[46] N. Khalili-Mahani, A. Assadi, K. Li, M. Mirgholami, M.-E. Rivard, H. Benali, K. Sawchuk, and B. D. Schutter, ''Reflective and reflexive stress responses of older adults to three gaming experiences in relation to their cognitive abilities: Mixed methods crossover study,'' *JMIR Mental Health*, vol. 7, no. 3, 2020, Art. no. e12388.

[47] Y. Ajaya, A. D. Peckham, and S. L. Johnson, ''Emotion regulation and mania risk: Differential responses to implicit and explicit cues to regulate,'' *J. Behav. Therapy Experim. Psychiatry*, vol. 50, pp. 283–288, Mar. 2016.

[48] F. Pallavicini, A. Pepe, and M. E. Minissi, ''Gaming in virtual reality: What changes in terms of usability, emotional response and sense of presence compared to non-immersive video games?'' *Simul. Gaming*, vol. 50, no. 2, pp. 136–159, Apr. 2019.

[49] R. Teixeira Soares, E. Sarmanho, M. Miura, T. Barros, R. Jacobi, and C. Castanho, ''Biofeedback sensors in electronic games: A practical evaluation,'' in *Proc. 16th Brazilian Symp. Comput. Games Digit. Entertainment (SBGames)*, Nov. 2017, pp. 56–65.

[50] Q. Yu, X. Che, S. Ma, S. Pan, Y. Yang, W. Xing, and X. Wang, ''A hybrid user experience evaluation method for mobile games,'' *IEEE Access*, vol. 6, pp. 49067–49079, 2018.

[51] S. Schmidt, S. Uhrig, and D. Reuschel, ''Investigating the relationship of mental immersion and physiological measures during cloud gaming,'' in *Proc. 12th Int. Conf. Quality Multimedia Exper. (QoMEX)*, May 2020, pp. 17–22.

[52] Y. Yoshida, I. Kaneko, and E. Yuda, ''Evaluation of eardrum temperature and autonomic nervous activity by VR motion sickness in amusement Park's VR attraction,'' in *Proc. 14th Int. Symp. Med. Inf. Commun. Technol. (ISMICT)*, May 2020, pp. 1–6.

[53] T. Appel, N. Sevcenko, F. Wortha, K. Tsarava, K. Moeller, M. Ninaus, E. Kasneci, and P. Gerjets, ''Predicting cognitive load in an emergency simulation based on behavioral and physiological measures,'' in *Proc. Int. Conf. Multimodal Interact.*, Oct. 2019, pp. 154–163.

[54] C. Rico-Olarte, D. M. López, L. Becker, and B. Eskofier, ''Towards classifying cognitive performance by sensing electrodermal activity in children with specific learning disorders,'' *IEEE Access*, vol. 8, pp. 196187–196196, 2020.

[55] M. Klarkowski, D. Johnson, P. Wyeth, C. Phillips, and S. Smith, ''Psychophysiology of challenge in play: EDA and self-reported arousal,'' in *Proc. CHI Conf. Extended Abstr. Hum. Factors Comput. Syst.*, May 2016, pp. 1930–1936.

[56] C. Holmgard, G. N. Yannakakis, H. P. Martinez, and K.-I. Karstoft, ''To rank or to classify? Annotating stress for reliable PTSD profiling,'' in *Proc. Int. Conf. Affect. Comput. Intell. Interact. (ACII)*, Sep. 2015, pp. 719–725.

[57] L. M´uller, A. Bernin, S. Ghose, W. Gozdzielewski, Q. Wang, C. Grecos, K. von Luck, and F. Vogt, "Physiological data analysis for an emotional provoking exergame," in *Proc. IEEE Symp. Ser. Comput. Intell. (SSCI)*, Dec. 2016, pp. 1–8.
[58] T. Terkildsen and G. Makransky, "Measuring presence in video games: An investigation of the potential use of physiological measures as indicators of presence," *Int. J. Hum.-Comput. Stud.*, vol. 126, pp. 64–80, Jan. 2019.
[59] M. Simões, M. Bernardes, F. Barros, and M. Castelo-Branco, "Virtual travel training for autism spectrum disorder: Proof-of-concept interventional study," *J. Med. Internet Res.*, vol. 20, no. 3, pp. 1–13, 2018.
[60] S. Kawaguchi, H. Mizoguchi, R. Egusa, Y. Takeda, E. Yamaguchi, S. Inagaki, F. Kusunoki, H. Funaoi, and M. Sugimoto, "EDA sensor-based evaluation of a vegetation succession learning system," in *Proc. 12th Int. Conf. Sens. Technol. (ICST)*, Dec. 2018, pp. 353–357.
[61] C. E. Stevens and D. L. Zabelina, "Creativity comes in waves: An EEG-focused exploration of the creative brain," *Current Opinion Behav. Sci.*, vol. 27, pp. 154–162, Jun. 2019.
[62] I. Amjad, H. Toor, I. K. Niazi, S. Pervaiz, M. Jochumsen, M. Shafique, H. Haavik, and T. Ahmed, "Xbox 360 Kinect cognitive games improve slowness, complexity of EEG, and cognitive functions in subjects with mild cognitive impairment: A randomized control trial," *Games Health J.*, vol. 8, no. 2, pp. 144–152, Apr. 2019.
[63] Q. Liu, X. Zhu, A. Ziegler, and J. Shi, "The effects of inhibitory control training for preschoolers on reasoning ability and neural activity," *Sci. Rep.*, vol. 5, no. 1, pp. 1–11, Nov. 2015.
[64] M. Välimäki, M. Yang, Y. T. J. Lam, T. Lantta, M. Palva, S. Palva, B. Yee, S. H. Yip, K.-S.-D. Yu, H. C. C. Chang, P. Y. I. Cheng, and D. Bressington, "The impact of video gaming on cognitive functioning of people with schizophrenia (GAME-S): Study protocol of a randomised controlled trial," *BMC Psychiatry*, vol. 21, no. 1, pp. 1–12, Dec. 2021.
[65] J. P. Dmochowski, J. J. Ki, P. DeGuzman, P. Sajda, and L. C. Parra, "Extracting multidimensional stimulus-response correlations using hybrid encoding-decoding of neural activity," *NeuroImage*, vol. 180, pp. 134–146, Oct. 2018.
[66] B. Yazmir and M. Reiner, "I act, therefore I err: EEG correlates of success and failure in a virtual throwing game," *Int. J. Psychophysiol.*, vol. 122, pp. 32–41, Dec. 2017.
[67] T. Mondéjar, R. Hervás, E. Johnson, C. Gutierrez, and J. M. Latorre, "Correlation between videogame mechanics and executive functions through EEG analysis," *J. Biomed. Informat.*, vol. 63, pp. 131–140, Oct. 2016.
[68] T. Mcmahan, I. Parberry, and T. D. Parsons, "Modality specific assessment of video game player's experience using the emotiv," *Entertainment Comput.*, vol. 7, pp. 1–6, Mar. 2015.
[69] É. Labonté-LeMoyne, P.-M. Léger, B. Resseguier, M.-C. Bastarache-Roberge, M. Fredette, S. Sénécal, and F. Courtemanche, "Are we in flow neurophysiological correlates of flow states in a collaborative game," in *Proc. CHI Conf. Extended Abstr. Hum. Factors Comput. Syst.*, May 2016, pp. 1980–1988.
[70] A. S. Blignaut and G. Matthew, "Part II: Survive with vuvu on the vaal: Electroencephalography results of a gameplay experience evaluation of a mobile serious game for statistics education," in *Proc. 16th World Conf. Mobile Contextual Learn.*, Oct. 2017, pp. 1–6.
[71] E. P. Núñez Castellar, J. N. Antons, D. Marinazzo, and J. Van Looy, "Mapping attention during gameplay: Assessment of behavioral and ERP markers in an auditory oddball task," *Psychophysiology*, vol. 56, no. 7, pp. 1–13, 2019.
[72] U. Ghani, N. Signal, I. K. Niazi, and D. Taylor, "A novel approach to validate the efficacy of single task ERP paradigms to measure cognitive workload," *Int. J. Psychophysiology*, vol. 158, pp. 9–15, Dec. 2020.
[73] D. J. Diaz-Romero, A. M. R. Rincon, A. Miguel-Cruz, N. Yee, and E. Stroulia, "Recognizing emotional states with wearables while playing a serious game," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–12, 2021.
[74] H. Aliyari, H. Sahraei, M. Erfani, M. Mohammadi, M. Kazemi, M. R. Daliri, B. Minaei-Bidgoli, H. Agaei, M. Sahraei, S. M. A. S. Hosseini, E. Tekieh, M. Salehi, and F. Farajdokht, "Changes in cognitive functions following violent and football video games in young male volunteers by studying brain waves," *Basic Clin. Neurosci.*, vol. 11, no. 3, pp. 279–288, 2020.
[75] L. Ghosh, S. Saha, and A. Konar, "Bi-directional long short-term memory model to analyze psychological effects on gamers," *Appl. Soft Comput.*, vol. 95, Oct. 2020, Art. no. 106573.
[76] T. Mcmahan, I. Parberry, and T. D. Parsons, "Evaluating player task engagement and arousal using electroencephalography," *Proc. Manuf.*, vol. 3, pp. 2303–2310, Jan. 2015.
[77] W. Auccahuasi, M. Díaz, F. Sernaque, E. Flores, G. Aiquipa, G. Rojas, and N. Moggiano, "Analysis of the comparison of the levels of concentration and meditation in the realization of academic activities and activities related to videogames, based on brain computer interface," *Pervasive-Health Pervasive Comput. Technol. Healthc.*, 2019, pp. 154–157.
[78] J. Ko, S. W. Jang, H. T. Lee, H. K. Yun, and Y. S. Kim, "Effects of virtual reality and non-virtual reality exercises on the exercise capacity and concentration of users in a ski exergame: Comparative study," *J. Med. Internet Res.*, vol. 8, no. 4, pp. 1–8, 2020.
[79] T. A. Dennis-Tiwary, L. J. Egan, S. Babkirk, and S. Denefrio, "For whom the bell tolls: Neurocognitive individual differences in the acute stress-reduction effects of an attention bias modification game for anxiety," *Behaviour Res. Therapy*, vol. 77, pp. 105–117, Feb. 2016.
[80] M. Abujelala, C. Abellanoza, A. Sharma, and F. Makedon, "Brain-EE: Brain enjoyment evaluation using commercial EEG headband," in *Proc. 9th ACM Int. Conf. Pervasive Technol. Rel. Assistive Environ.*, Jun. 2016, pp. 1–5.
[81] A. T. Bayrak, M. Abernethy, Y. Zhu, Z. A. Lawati, and C. J. Sutherland, "Signal to emotion: An experiment on player experience evaluation with a consumer-grade EEG device," in *Proc. 29th Austral. Conf. Comput.-Hum. Interact.*, Nov. 2017, pp. 472–476.
[82] L. Xin, T. Yan-Xiu, Q. Xiao-Ying, and S. Xiao-Feng, "Stress state assessment by complexity and entropy," in *Proc. 6th Int. Conf. Instrum. Meas., Comput., Commun. Control (IMCCC)*, Jul. 2016, pp. 471–475.
[83] B. Wan, Q. Wang, K. Su, C. Dong, W. Song, and M. Pang, "Measuring the impacts of virtual reality games on cognitive ability using EEG signals and game performance data," *IEEE Access*, vol. 9, pp. 18326–18344, 2021.
[84] C. Verbaarschot, J. Farquhar, and P. Haselager, "Free wally: Where motor intentions meet reason and consequence," *Neuropsychologia*, vol. 133, Oct. 2019, Art. no. 107156.
[85] A. S. Ravindran, A. Mobiny, J. G. Cruz-Garza, A. Paek, A. Kopteva, and J. L. C. Vidal, "Assaying neural activity of children during video game play in public spaces: A deep learning approach," *J. Neural Eng.*, vol. 16, no. 3, Jun. 2019, Art. no. 036028.
[86] S. H. Kim, G. Buzzell, S. Faja, Y. B. Choi, H. Thomas, N. H. Brito, L. C. Shuffrey, W. P. Fifer, F. D. Morrison, C. Lord, and N. Fox, "Neural dynamics of executive function in cognitively-able kindergarteners with autism spectrum disorders (ASD) as predictors of concurrent academic achievement," *Autism*, vol. 24, no. 3, pp. 780–794, 2020.
[87] A. B. G. S. Fernandes, J. C. P. de Melo, D. C. de Oliveira, F. A. D. C. Cavalcanti, O. A. Postolache, P. J. M. Passos, and T. F. Campos, "Is motor learning of stroke patients in non-immersive virtual environment influenced by laterality of injury? A preliminary study," *J. Bodywork Movement Therapies*, vol. 25, pp. 53–60, Jan. 2021.
[88] N. S. Abd Rahman, M. Mustafa, R. Samad, N. Sulaiman, N. R. H. Abdullah, N. H. Noordin, A. A. Hadi, and S. N. A. S. Ahmad, "Initial experiment of muscle fatigue during driving game using electromyography," in *Proc. 7th IEEE Int. Conf. Syst. Eng. Technol. (ICSET)*, Oct. 2017, pp. 101–105.
[89] P. F. de Oliveira, D. H. Iunes, R. S. Alves, J. M. de Carvalho, F. S. da Menezes, and L. C. Carvalho, "Effects of exergaming in cancer related fatigue in the quality of life and electromyography of the middle deltoid of people with cancer in treatment: A controlled trial," *Asian Pacific J. Cancer Prev.*, vol. 19, no. 9, pp. 2591–2597, 2018.
[90] P. Soltani, P. Figueiredo, R. J. Fernandes, and J. P. Vilas-Boas, "Muscle activation behavior in a swimming exergame: Differences by experience and gaming velocity," *Physiol. Behav.*, vol. 181, pp. 23–28, Sep. 2017.
[91] N. Hesam-Shariati, T. Trinh, A. G. Thompson-Butel, C. T. Shiner, and P. A. McNulty, "A longitudinal electromyography study of complex movements in poststroke therapy. 2: Changes in coordinated muscle activation," *Frontiers Neurol.*, vol. 8, pp. 1–12, Jul. 2017.
[92] L. Paletta et al., "MIRA—A gaze-based serious game for continuous estimation of Alzheimer's mental state," in *Proc. Eye Tracking Res. Appl. Symp. (ETRA)*, 2020, pp. 1–3.
[93] G. R. Hellianto, B. M. Iqbal, and Komarudin, "Ergonomics evaluation of game interface design provisions on various computer based monitor screens," in *Proc. Int. Conf. Ind. Design Eng. (ICIDE)*, 2017, pp. 38–44.
[94] K. M. Roose, E. S. Veinott, and S. T. Mueller, "The tracer method: The dynamic duo combining cognitive task analysis and eye tracking," in *Proc. Annu. Symp. Comput.-Hum. Interact. Play Companion Extended Abstr.*, Oct. 2018, pp. 585–593.
[95] G. E. Raptis, C. Fidas, and N. Avouris, "Do game designers' decisions related to visual activities affect knowledge acquisition in cultural heritage games? An evaluation from a human cognitive processing perspective," *J. Comput. Cultural Heritage*, vol. 12, no. 1, pp. 1–25, Feb. 2019.

[96] M. Cutumisu, K.-L. Turgeon, T. Saiyera, S. Chuong, L. M. González Esparza, R. MacDonald, and V. Kokhan, ''Eye tracking the feedback assigned to undergraduate students in a digital assessment game,'' *Frontiers Psychol.*, vol. 10, pp. 1–13, Sep. 2019.

[97] M. A. Friehs, M. Dechant, S. Vedress, C. Frings, and R. L. Mandryk, ''Effective gamification of the stop-signal task: Two controlled laboratory experiments,'' *J. Med. Internet Res.*, vol. 8, no. 3, pp. 4–7, 2020.

[98] D. N. Mohd Nizam and E. L.-C. Law, ''Derivation of young children's interaction strategies with digital educational games from gaze sequences analysis,'' *Int. J. Hum.-Comput. Stud.*, vol. 146, Feb. 2021, Art. no. 102558.

[99] J. Y. Lee, J. Donkers, H. Jarodzka, and J. J. G. van Merriënboer, ''How prior knowledge affects problem-solving performance in a medical simulation game: Using game-logs and eye-tracking,'' *Comput. Hum. Behav.*, vol. 99, pp. 268–277, Oct. 2019.

[100] M. Taub, N. V. Mudrick, R. Azevedo, G. C. Millar, J. Rowe, and J. Lester, ''Using multi-channel data with multi-level modeling to assess in-game performance during gameplay with crystal Island,'' *Comput. Hum. Behav.*, vol. 76, pp. 641–655, Nov. 2017.

[101] S. Almeida, Ó. Mealha, and A. Veloso, ''Video game scenery analysis with eye tracking,'' *Entertainment Comput.*, vol. 14, pp. 1–13, May 2016.

[102] N. G. Murray, N. R. D'Amico, D. Powell, M. E. Mormile, K. E. Grimes, B. A. Munkasy, R. K. Gore, and R. J. Reed-Jones, ''ASB clinical biomechanics award winner 2016: Assessment of gaze stability within 24–48 hours post-concussion,'' *Clin. Biomechanics*, vol. 44, pp. 21–27, May 2017.

[103] C. Krebs, M. Falkner, J. Niklaus, L. Persello, S. Klöppel, T. Nef, and P. Urwyler, ''Application of eye tracking in puzzle games for adjunct cognitive markers: Pilot observational study in older adults,'' *J. Med. Internet Res.*, vol. 9, no. 1, Mar. 2021, Art. no. e24151.

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