

Diversity and Suitability of the State-of-the-Art Wearable and Wireless EEG Systems Review

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Abstract—Wireless electroencephalography (EEG) systems have been attracting increasing attention in recent times. Both the number of articles discussing wireless EEG and their proportion relative to general EEG publications have increased over years. These trends indicate that wireless EEG systems could be more accessible to researchers and the research community has recognized the potential of wireless EEG systems. To explore the development and diverse applications of wireless EEG systems, this review highlights the trends in wearable and wireless EEG systems over the past decade and compares the specifications and research applications of the major wireless systems marketed by 16 companies. For each product, five parameters (number of channels, sampling rate, cost, battery life, and resolution) were assessed for comparison. Currently, these wearable and portable wireless EEG systems have three main application areas: consumer, clinical, and research. To address this multitude of options, the article also discussed the thought process to find a suitable device that

meets personalization and use cases specificities. These investigations suggest that low-price and convenience are key factors for consumer applications, wireless EEG systems with FDA or CE-certification may be more suitable for clinical settings, and devices that provide raw EEG data with high-density channels are important for laboratory research. This article presents an overview of the current state of the wireless EEG systems specifications and possible applications and serves as a guide point as it is expected that more influential and novel research will cyclically promote the development of such EEG systems.

Index Terms—Wireless EEG systems, consumer, clinical and research applications, suitable devices.

I. INTRODUCTION

ELECTROENCEPHALOGRAPHY (EEG) is the measurement of electrical brain activity from the scalp. EEG is one of many in vivo neuroimaging modalities, which also include functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and electrocorticography (ECoG). Both fMRI and fNIRS measure brain oxygenation activity, while ECoG and EEG measure brain electrical activity. EEG systems are more widely used in neurocognitive research, brain dynamics and real-world applications due to its non-invasiveness, portability, compact design, and high temporal resolution [1], [2], [3]. EEG functional pattern potentially allow for the continuous monitoring of brain activity in real-world environments.

Brain-computer interfaces (BCI) are emerging technology in the field of neuroscience that facilitates interaction between a user and a computer or the outside environment by interpreting signals generated in the brain [4]. Traditionally, the definition of active BCI refers to voluntary modulation of brain activity to interact with the environment [5], [6]. A great amount of research has investigated the possibility of using EEG for real-world applications. Active BCI are mainly used for the control of exoskeletons, robotic arms, cursors, computer spellers, as well as for human photographs authentication system [7], [8], [9], [10]. Comparatively, passive BCI refer to encompass the monitoring and interpretation of spontaneous cognitive and emotional states, such as attention, fatigue, concentration, and stress [11], [12], [13]. Several findings in the literature have proposed the use of passive BCI to monitor mental states, such as drowsiness, sleep deprivation, and attention [14], [15]. Recent studies have also proposed the use of BCI as biometric authentication, which

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TABLE I
TECHNICAL SPECIFICATIONS AND BASIC INTRODUCTION OF THE WIRELESS EEG SYSTEMS

Devices	Systems cost (USD)	Electrodes sensor	Sensor cost	Channels	Sampling rate (Hz)	Resolution (Bits)	Battery life (Hours)	Certification	Announcement	Aggregated measures
(A) B-Alert X-24	~20k	Passive; Multi-use; Gel-based sponge disks;	Middle	20	256	16	8	FDA	2011	Cognitive state and Workload models
(B) Quick-20m	~25k	Passive; Multi-use; Dry electrodes;	High	20	500	24	6	FDA	2021	--
(C) DSI 24	22k-25k	Active, Multi-use, Hybrid resistive-capacitive sensors;	N/A	24	300/600	16	8	--	2013	Mental workload, Engagement, Fatigue
(D) LiveAmp	~22k (+)	Active/ Passive; Multi-use, Dry sponge solid /Gel;	Middle	8/16/32 /64	250/500 /1000	24	10	--	2015	--
(E) g. Nautilus pro	7600(+)	Active, Multi-use, Dry 8 gold-alloy coated pins/Gel;	Middle	8/16/32	500	24	10	CE & FDA-	2017	* ³ Emotional response
(F) Smarting	~6100	Passive; Multi-use; Gel-based ring;	Middle	24	250/500	24	5	---	2013	--
(G) Enobio	6000(+)	Passive; Multi-use; Dry/ NG Gel;	Middle	8/20/32	500	24	5.5	CE	2016	Human experience, Human performance Biomarker discovery Attention, Memory, Concentration.
(H) LOOXIDVR	2999	Passive; Multi-use; Flexible printed circuit board (FPCB) electrodes;	Low	6	250/500 /1000	24	Depends on your phone	--	2018	Excitement, Engagement, Stress, Cognitive Load, Interest
(I) EPOC ^x	1917 * ¹	Passive; Multi-use; Saline soaked felt pads;	Middle	14	2048	14/16	9	--	2020	--
(J) Altaire	1880	Passive; Multi-use; Moisture sponge electrodes/ Spring-loaded metal;	Middle	8	1000	24	10	--	2018	--
(K) The All-in-One Electrode Cap Kit	2449	Active/ Passive; Multi-use, Gel electrodes;	Middle	16	125	24	10	--	2019	--
(L) Unicorn hybrid black	1100	Passive; Multi-use; Hybrid EEG electrodes	High	8	250	24	2	--	2019	--
(M) Mindo BR8	899	Passive; Multi-use; Moisture sponge electrodes/ Spring-loaded metal;	Middle	8	500/1000	24	10	--	2015	--
(N) MindWav Mobile 2	598 * ²	Passive; Multi-use; Embeddable biosensor	Low	1	512	12	8	--	2018	Attention, Meditation, Emotional Spectrum
(O) MINDROVE	729	Passive; Multi-use; Semi-dry electrodes;	Low	6	500	24	3	--	2019	--
(P) Muse2	249	Passive; Multi-use; Silver (frontal electrodes), conductive silicone rubber (temporal electrodes);	Low	4	256	12	5	--	2018	Mind meditation

*¹: unit cost + 1 year subscription fees. *²: headset cost + research tool fees. *³ additional purchase

achieved notable subject identification performance [16], [17]. These exciting studies show the broad application areas of BCI technologies.

Most BCI studies have been carried out using wired EEG systems, where an EEG cap is tethered to a stationary power supply unit, standalone amplifier, and data recording computer. This is suboptimal and inconvenient for real-world applications, as device portability is a crucial criterion for implementing BCI technology in real-world settings. More recently, research has started to shift from wired to wireless EEG systems. To keep up with the increasing demand, many technological firms have

designed and marketed novel wireless EEG systems, which are listed in Table I, including Advanced Brain Monitoring (ABM) [A], Cognionics [B], QUASAR [C], Brain Products [D], g.Tec[E] and so on. EEG signals recorded from wireless EEG systems have been successfully used to control mobile robots [18] and alarm sleepy drivers [19]. A general-purpose wireless EEG device called PennBMBI was developed to provide real-time EEG monitoring and easy user configuration [20]. I Wireless EEG systems have been used in the context of entertainment to play tactical video games using steady-state evoked potentials (SSVEP) [2]. These applications demonstrate

the wide range of applications for which wireless EEG systems can be used.

A recent review article summarized the evolution of EEG-based BCIs from the perspective of encoding paradigms and decoding algorithms [21]. Another evaluation using noninvasive mobile EEG equipment examined the most recent clinical and research trials with epilepsy or suspected seizures. [22]. X. Gu et al. [23] reviewed the new literature on EEG signal detection technologies and computational intelligence approaches in BCI applications. Despite some studies evaluating the technologies, algorithms, and part-of applications of EEG-based BCIs, to our knowledge, there has yet to be a large-scale study reviewing the specifications and applications of wireless EEG systems. To facilitate the choice of wireless EEG systems for research and other applications, we offer a comprehensive review of the specifications and possible applications of marketed wireless EEG systems. This study will discuss 16 wireless EEG systems marketed by companies, with the main objectives of this review being:

- 1) To explore the current research trends of wireless EEG systems, in comparison to wired devices (Section II).
- 2) To survey a large number of wireless EEG systems and discuss their respective specifications, for facilitating future choices of EEG devices (Section III).
- 3) To review the literature describing or proposing applications of wireless EEG systems, giving readers an overview of the potential for incorporating wireless EEG systems into a variety of situations (Section IV).
- 4) To provide insight into the thought process for choosing a wireless device suitable for users' combined personalization and use cases specificities (Section V).

II. TRENDS OF WIRELESS EEG SYSTEMS

Based on the Neurotechnologies & Brain-Computer Interface report from Yole [24], the compound annual growth rate (CAGR) of the BCI market is growing from 18.66% during the 2017–2023 period, to 30.56% in 2023–2029, and is estimated to achieve 48.75% in 2029–2035. Fig. 1 shows the increasing popularity and demand for BCI technologies, potentially reaching widespread adoption in the near future. This phenomenon will certainly accelerate the research and development of BCI technology for various applications. However, conventional, wired EEG systems are not user-friendly for real-life applications, they pose particular inconveniences such as limited mobility, wires entanglement, and user tripping. Recent advancement in wireless EEG systems has allowed for drastic improvement of device portability, in the hope of providing more user flexibility.

A literature survey was performed to highlight the research trends of wireless EEG systems over the past 14 years. The total number of articles, within the years 2008 to 2021, which contain the keyword 'EEG' was acquired by searching Google Scholar. The keyword 'Wireless EEG' was searched to enumerate wireless EEG systems related articles. We removed non-related articles in which the search keywords were only present as part of an author's name.

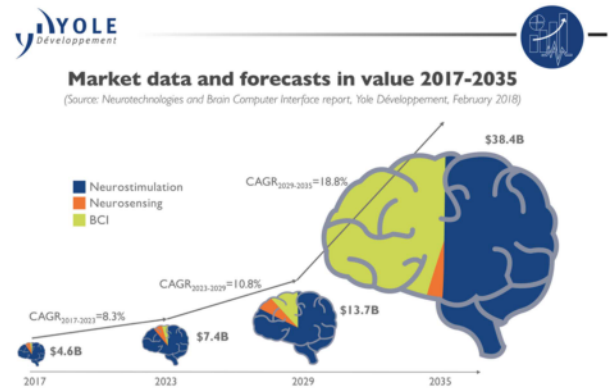


Fig. 1. Yole développement: Neurotechnologies and brain computer interface report 2018. A neurotechnology market analysis shows increasing trend in the commercialization of BCI technologies from year 2017 to 2035 [24].

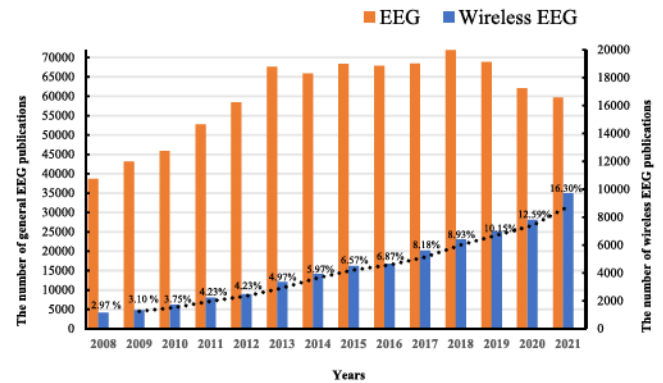


Fig. 2. Total number of general and wireless EEG publications over the last 14 years searched by Google Scholar. Wireless EEG is an increasingly popular research topic. (The publications up to December 2022).

Based on publications between 2008 and 2021, after peaking in the middle of the decade, the number of general EEG publications has exhibited decline slightly since 2019. In contrast, there has been an increasing amount of research focused on wireless EEG systems, shown in Fig. 2. The number of articles discussing wireless EEG published each year has increased from 1150 publications in 2008 to 7810 in 2020, and 9720 in 2021. The wireless EEG to general EEG research ratio increased from 2.97% in 2008 to 12.59% (2020) and 16.30% (2021). Several variables may have contributed to the increase in publications. First, as the market for wireless EEG expands, researchers may have easier access to this technology. Additionally, these intriguing results imply that the scientific community has begun to recognize the potential of wireless EEG devices and that greater focus is now being placed on the implementation of wireless BCIs in practical applications. So, this research trend provides further motivation for us to survey the contemporary EEG systems commercially available, and compare their specifications.

III. WIRELESS EEG SYSTEMS

Non-invasive wireless EEG systems are relatively quick to set up and easy to use [25]. Such a device could be conveniently carried to monitor brain activity outside the laboratory and is, therefore, more suitable for real-world environments [25] than other types of brain monitoring systems. In this section, we surveyed a large number of commercially available wireless EEG systems and compared their respective specifications. Our criteria for selecting products are systems available in the market rather than at the start-up fundraising stage. For each company's product, we only choose a representative product. The selected products should have more relevant publications.

We conducted extensive searches to identify companies' offerings of wearable EEG devices. From this 16 wireless EEG systems were selected, marketed from 16 companies, which are depicted and characterized in Fig. 3.

The official websites and manufacturers from which the specifications of 16 wireless EEG systems were obtained are cataloged in the Device Index Section. The wireless EEG systems included in this study are the: B-Alert X-24 from Advanced Brain Monitoring (ABM) [A], Quick-30 from Cognionics [B], Dry Sensor Interface (DSI) 10–20 from QUASAR [C], LiveAmp from Brain Products [D], g.Nautilus with g.SAHARA from g.Tec[E], Smarting from mBrainTrain [F], Enobio from Neuroelectrics [G], LooxidVR from LooxidVR Labs [H], the EPOC^X from Emotiv Systems[I], Altaire from Artise[J], The All-in-One Electrode Cap Kit from OpenBCI [K], Unicorn hybrid black from Unicorn Brain Interface [L], BR8 from Mindo [M], MindWave Mobile 2 from NeuroSky[N], MINDROVE [O], Muse2 from InteraXon [P]. There is a linked list of all wireless EEG systems in Appendix at the end of this article.

Fig. 3 is an index chart of the selected 16 wireless EEG systems. Table I details each system's cost, electrode sensors type, sensor cost, channel number, sampling rate, battery life, bit resolution, certification information, year of model release and aggregated measures. All the data we reported are based on the specifications released by each vendor. The relevant metrics of the number of channels, sampling rate, cost, battery life, and resolution are summarized in a pentagon plot for each product. For a device in a particular product series, the device with the lower number of channels, sample rate, or starting price was selected. Due to the large price variance between devices, log normalization was performed where the logarithmic price was divided by the maximum logarithmic price (\$30000). The other parameters were also normalized (eg. device channel number divided by max channel number). Asterisks indicate that special information was found for that particular parameter. The wireless devices were sorted by approximate system price, and devices without price information are placed at the end of the table. To improve readability, each device (and corresponding company) was given a unique identification letter that is utilized consistently throughout the review. The specifications of all wireless EEG systems were arranged as in Fig. 3, and classified according to the electrode types available for the devices, which are dry electrodes, wet electrodes, and customizable electrode type.

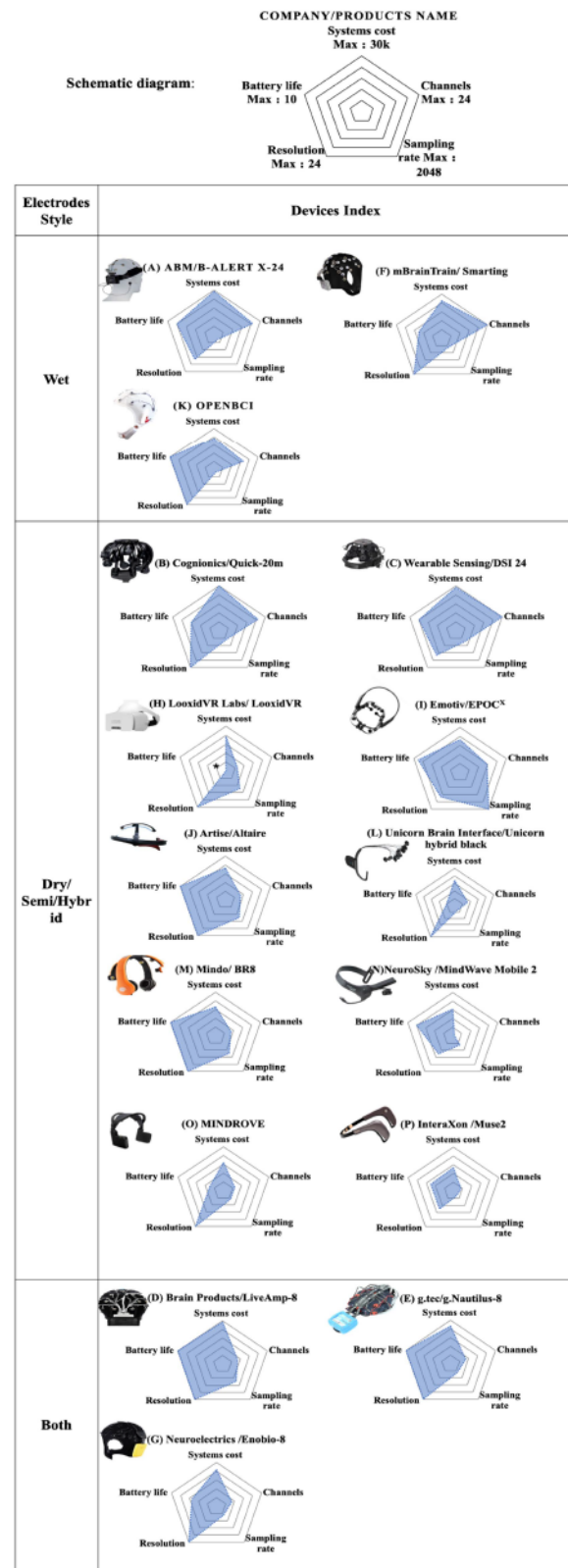


Fig. 3. Devices index. (a) AdvancedBrainMonitoring/B-Alert X-24; (b) Cognionics/Quick-20m; (c) Wearable Sensing/DSI-24; (d) Brain Products/LiveAmp; (e) g.Tec/g.Nautilus; (f) mBrainTrain/Smarting; (g) Neuroelectrics/enobio; (h) LooxidVR Labs/LooxidVR; (i) Emotiv/EPOC^X; (j) Artise/altair; (k) OpenBCI/the all-in-one electrode cap kit; (l) Unicorn brain interface/unicorn hybrid black (m) Mindo/BR8; (n) NeuroSky/MindWave mobile 2; (o) Mindrove; (p) InteraXon/Muse2

ABM makes an EEG system (B-Alert X-24) [A] with 20 gel-based, sponge disk electrodes, costing around 22k USD; it's focused on providing quality products to customers in the US market for physiological monitoring of troops, in-home sleep research, and war scenarios. In addition, it has been approved by the US Food and Drug Administration (FDA) for use as a medical device [26]. The Cognionics Quick-20m [B] systems cost around 3k USD for 20 channels, with dry polymer electrodes. They also have Quick-8 and Quick-30 series (8 and 30 channels, respectively.) Quick-20m has been approved by the US FDA, and claim the Quick series is comparable to other research-grade EEG systems. QUASAR makes an EEG system (DSI-24) [C] with 24 hybrid resistive-capacitive sensors and they claim it is ready to record EEG within 5 minutes, and costs over 22k USD. Their patented technologies, including shielding, circuit design, and common mode cancellation, reduce static noise and motion artifacts to further enable high-quality, dynamic data acquisition in electronically noisy environments. The Brain Products LiveAmp [D] costs around 22k USD for a minimum of 8 channels, with dry sponge solid-gel electrodes. In addition, the LiveAmp series is a Conformite Europeenne (CE)-certified mobile EEG system.

The g.Tec [E] [27] wireless g.Nautilus pro systems cost from 7.6k to 25k USD, for a minimum of 8 channels, with active dry gold-alloy coated pins (g.SAHARA) or active wet electrodes (g.LADYbird). In addition to the research version of g. Nautilus, they also have a CE-certified and FDA-cleared medical version, the g. Nautilus-PRO[E]. The mBrainTrain manufactured Smarting headsets, with gel-based ring electrodes, which cost around 6.1k USD for 24 channels [F]. It uses wet gel-electrodes. For mobile applications, it can connect to a personal computer or mobile phone to monitor brain activity outside the laboratory. The Enobio [G] systems use passive dry electrodes or solid-gel electrodes from 6k to 27k USD, costing 6k USD for a minimum of 8 channels, and their amplifiers are CE medically certified [27]. LooxidVR [H] offers a headset with foam pads and six flexible printed circuit board electrodes, costing around 3k USD. Its unique feature is that it can collect the user's eye and brain data simultaneously during a VR experience; its battery life depends on the connected phone. The Emotiv [I] EPOC^X, which was awarded the Reddot award, uses saline-soaked felt pads, costs 849 USD for 14 channels, is designed for scalable and contextual human brain research, and provides access to professional-grade brain data, along with a quick and 'easy to use' design. However, in order to get the raw EEG data, the purchase of Emotiv pro software license (1068 USD annual subscription) is needed. From the literature survey, we can observe that Emotiv has applications in research, real world, and medical fields. The purchase of a non-commercial subscription license for one year is \$1068. A newer company, Artise Biomedical Co., makes an EEG headset (Altaire) with moisture sponge electrodes and spring-loaded metal electrodes, costing over 1.8k USD for 8 channels [J]. We can see All-in-One Electrode Cap Kit from OpenBCI's [K] official website, the product uses gel electrodes, costing over 2.49k USD for 16 channels. Their free software can provide free raw data. They also sell Daisy Biosensing Boards

and EEG headsets along with other parts for self-assembly. Unicorn Brain Interface has recently released a 1.1k USD version that is the Unicorn hybrid black. By using eight unicorn hybrid EEG electrodes, it claims to offer high-quality and accurate EEG recordings for various applications such as art, neuroscience, or neuromarketing [L]. The Mindo BR8 device can accommodate moisture sponge, foam-based, and/or spring-loaded metal electrodes. It has a unique earphone form factor, costing 899 USD for 8 channels. Additionally, the devices also can be used in the real-world, clinical, and laboratory research [M]. NeuroSky [N] is available at a lower price, with a headset costing only 99 USD, using a single channel for measurement and making it easy to use. Accessing the raw EEG signals can be obtained by purchasing their research tool that costs 499 USD. With this type of device, users can record mental states during meditation and track attention levels. Mindrove [O] uses semi-dry electrodes that need a few drops of saline water for a proper connection, and costs around 729 USD for 6 channels, rather than using a Bluetooth connection, the headband uses Wi-Fi to communicate with other devices. The Muse 2 [P] is a 4-sensor meditation-tracking device, and its sensors are all located near the prefrontal areas. It can provide real-time feedback on brain activity, heart rate, breathing, and body movements to help users develop consistent meditation exercises.

We attempted to include a wide array of wireless EEG systems and companies for systematic comparison, resulting in the 16 detailed above. In addition to these, the wireless EEG systems of three other companies, Imec, Zeto, and Ant neuro, were investigated. These were not included in Fig. 3 or Table I because some parameters about these devices (such as prices, etc) were not publicly accessible, but are summarized below for reference. For example, the Imec [Q] EEG headset uses eight, dry and flexible, conductive, polymer electrodes. Its EEG platform include an EEG headset and an EEG data-analysis platform. The special feature of this device is that it includes a headphone jack; with the help of artificial intelligence, the device can learn the personal music preferences of the wearer, and play music that suits the wearer's preferences. The Zeto EEG headset [R] uses 19 dry electrodes; the company claims that they are the first true, dry-electrode EEG systems cleared for clinical use by the FDA. ANT Eego sports [S] is CE marked as a medical device in the EU. The news release in 2019 showed that the new Eego sports has 128 channels and uses Ag/AgCl coated soft polymer electrodes to provide stable EEG signals.

As shown, the price of wireless devices ranges from 240 to 30000 USD. We classify the cost into three categories, which are high (above 10000 USD), middle (between 1000 USD and 10000 USD), and low (below 1000 USD) price. Out of 16 devices, 12 of them are grouped as middle and low cost. Battery life varies from 3 hours to 10 hours. Various sensor types have been developed, including dry sensor, wet, and semi-dry sensors. The sensor turnover cost may be categorized into three levels according to the number of replacements needed and their prices. The sensors that need to be changed frequently with a unit price cost of more than 5 USD are considered a high price, wet gel and sensors with a unit price less than 5 USD are defined as in the middle

price range. The sensors that don't need to be changed are in the low-price range.

As wireless EEG systems have become more diverse, the applications of these EEG devices have widened. Some of the EEG systems have been approved by FDA or CE for clinical research, and some affordable consumer devices have been marketed for entertainment purposes. The technologies of VR and/or music, and breathing, heartbeat, and eye-tracking are also being integrated into newly developed products. This section provided a comprehensive review of the specifications for numerous marketed EEG devices, aiming to provide references for researchers in selecting suitable wireless EEG systems in their studies.

IV. THE APPLICATIONS OF WIRELESS EEG SYSTEMS

In this section, we focus on the applications of portable wireless EEG systems. To assess particular system usages, we conducted extensive searches on Google Scholar with relevant keywords: 'Company name + EEG'; for example, 'Cognionics EEG' or 'Mindo EEG'. For each wireless EEG product, we selected relatively well-cited articles across different research themes. Some wireless EEG devices are used in relatively new publications were also selected. As a result, a total of 44 papers are detailed in Table II. Although it is not an exhaustive list, it represents an overview of some important key roles in which wireless EEG systems are employed. Table II summarizes the application field (e.g., consumer application), the publishing information (e.g., author, title, cited number and the cited number up to January, 2023), the research theme (e.g., driving, stress), and the wireless EEG manufacturing company (e.g., Emotiv) for the chosen papers. Except for the Artise and Mindrove systems, which were announced in the past two years, and as of yet, have no publication history, various articles were found for the other 14 companies. After studying the contents of all the selected papers, some general trends in the research applications were evident. One of the identifiable applications was consumer study, which encompasses investigations around real-world physiological monitoring, gaming, and communication. In addition, it was found that the diagnosis, prevention, and treatment of diseases were also accomplished by using wirelessly monitored EEG signals in clinical settings. Wireless EEG systems were also found in many studies in neuroscience and signal processing. We consequently grouped their applications into three main corresponding categories: consumer, clinical, and research.

A. Consumer Applications

We categorize wireless EEG system publications into four classes for consumer applications (mostly uses in real-world settings): cognitive and affective state monitoring, entertainment, education and technology, and communication. One of the most significant real-world applications for wireless EEG devices is cognitive and emotional state monitoring. Research topics include alertness, drowsiness, stress, attention, emotions, memory, and others.

1) Cognitive and Affective State Monitoring: In the real world, the cognitive and affective state monitoring is one of the most important application areas for wireless EEG systems, the research themes include alertness, drowses, stress, attention, emotions, memory, and so on.

As an illustration, Lin et al. [1] used the wireless Mindo headset to monitor EEG activity, and proposed a system to monitor driving fatigue in real-time, as part of an experiment involving 15 research participants during 90 minutes of immersive virtual driving. Utilizing signals derived from participants' constant attention towards driving tasks and the environment, they successfully developed a driver alertness-monitoring system. Another study that utilized Mindo was developed by Kelliher et al. [28], which proposed a multifaceted integration of neuroimaging systems designed to overcome real-world and neuroimaging barriers. It combined autonomic nervous system-related physiological responses with neurological data and subjective measurements. This technique could help researchers to better understand neural mechanisms in the real world.

A recent study by Zheng et al. [29] combined EEG signals with eye-tracking information and proposed a composite emotion recognition framework that was presented at the Consumer Electronics Show (CES) 2016. The Looxid Labs system integrates eye-tracking and two frontal EEG electrodes into a headset to record EEG signals and pupil dilation simultaneously. Mohammadpour et al. [30] divided emotions into six categories (fear, sad, frustrated, happy, pleasant and satisfied), and used OpenBCI to collect emotion-indicative EEG signals, with machine learning to classify the resulting data. Aspinall et al. [31] used Emotiv to record and analyze the emotional experiences of the walkers in three urban environments (streets, green spaces, commercial districts). It is one of the earliest studies to use mobile EEG systems and EEG-based emotion recognition software to record emotional changes in people freely walking in a city environment. Karran et al. [32] utilized data collected by the Enobio system and psychophysiological data to infer visitors' states of interest toward cultural heritage materials. This system aimed to maintain the interest of visitors. Mullen et al. [33] and Callan et al. [34] used Cognionics for neuroimaging and cognitive monitoring. Mullen's study incorporated real-time measurement and interpretation of complex brain activity collect by a wearable device in a dynamic environment. Callan et al. [34] conducted their study on motion-platform flight simulators and actual flights of open-cockpit biplanes, classifying the events the pilots' perceived. Additionally, two separate articles by Berka et al., based on ABM (B-Alert) systems, contributed to research on cognitive workloads. The first one [35] described research consisting of 45 participants whose EEG signals were analyzed in real-time to monitor indicators of alertness, cognition, and memory. It discussed possible future applications for enhancing cognition in military and industrial environments. The second study [36] investigated the feasibility of using the B-Alert X-24 system to monitor mental workload and engagement levels in image, verbal and interference learning, memory, digit span, and vigilance tests. The results showed that workload-related EEG activities and mean subjective rating scores were related,

TABLE II
THE CURRENT APPLICATIONS OF WIRELESS EEG SYSTEMS

Applications	Sample Publications	Cited number	Theme	Manufacture company
Consumer Application	Lin. et al. (2014)	228	Alertness/drowses	Mindo (M)
	Kellihaan. et al. (2013)	14	Stress	Mindo (M)
	Zheng. et al. (2018)	406	Attention	Looxid (H)
	Mohammadpour. et al. (2017)	42	Emotions	OpenBCI (K)
	Aspinall. et al. (2015)	635	Emotions	Emotiv (I)
	Mullen. et al. (2015)	501	Cognitive monitoring	Cognionics (B)
	Callan. et al. (2015)	57	Auditory stimulus	Cognionics (B)
	Berka. et al. (2004)	514	Alertness/Cognitive	ABM (A)
	Berka. et al. (2007)	1039	Task Engagement and Mental Workload	ABM (A)
	Karran. et al. (2015)	17	Knowledge emotion	Neuroelectrics (G)
Consumer Application	Zao. et al. (2014)	157	Gaming	Mindo (M)
	Abujelala. et al. (2016)	65	Gaming	InteraXon (P)
	Badcock. et al. (2013)	444	Gaming	Emotiv (I)
	Zink, Rob, et al. (2016)	97	Sports	mBrainTrain (F)
	Hashemi, Ali, et al. (2016)	85	Meditation exercises	InteraXon (P)
	Xu, Jiahui, and Baichang Zhong. (2018)	130	Educational Technology	Emotiv (I) /Neurosky (N)
	Abbate, Stefano, Marco Avvenuti, and Janet Light. (2014)	58	Wireless Monitoring System	Neuroelectrics (G)
	Orhan, Umut, et al. (2012)	127	Typing interface	g.tec (E)
	Debener, Stefan, et al. (2015)	305	Behind-the-ear electrode array	mBrainTrain (F)
	Kwak. et al. (2015)	205	Lower limb exoskeleton control systems	Brain Products (D)
Clinical Applications	Perera. et al. (2017)	34	Meal Assistance Robot	OpenBCI (K)
	Stephygraph. et al. (2016)	95	Eye blink/Attention detection	NeuroSky (N)
	Krishnan. et al. (2016)	14	Control robots	Emotiv (I) /NeuroSky (N)
	Katona, Jozsef, et al. (2016)	97	Control robots	/Mindo (M)
	Sterr. et al. (2018)	54	Sleep physiology	NeuroSky (N)
	Lin. et al. (2017)	50	Headache prevention	mBrainTrain (F)
	O'Sullivan, Mark, et al. (2017)	12	Epilepsy	Mindo (M)
	Biondi, Andrea, et al. (2022)	6	Epilepsy	Emotiv (I)
	Cao. et al. (2019)	88	Migraine	Enobio 8 · Eego · Emotiv EPO
	Alchalabi. et al. (2018)	62	Adhd	Mindo (M)
Research Application	Berger, Theodore W., et al. (2008)	25	Rehabilitation	Emotiv (I)
	Wipprecht, Anouk. (2019)	1	ADHD	g. Tec (E) /QUASAR (C)
	Lee. et al. (2013)	74	Medical, Neurofeedback	Unicorn (L)
	Cao. et al. (2018)	52	Depression	Neuroelectrics (G)
	Melnik. et al. (2017)	88	ERP · SSVEP	Mindo (M)
	Placidi. et al. (2015)	50	Olfactory stimulation research	g. Tec (E) /Brain Products (D)
	Radüntz, Thea. (2018)	85	Signal quality	/Emotiv (I)
	Mullen. et al. (2013)	317	Reliable real-time modeling	Neuroelectrics (G)
	Minguillon. et al. (2017)	247	Artifact removal	Cognionics (B)
	Hairston. et al. (2014)	224	Comparison EEG systems	g. Tec (E)
Research Application	Di Flumeri. et al. (2019)	121	Evaluation dry electrodes	Wearable Sensing (C)
	Zander. et al. (2011)	160	Evaluation signal quality	/Emotiv (I) / ABM (A)
	Brown. et al. (2010)	86	Comparison EEG systems	Wearable Sensing (C) /Brain products (D)
	Estepp, Justin R, et al. (2009)	65	Validation signal quality	Brain products (D)
				ABM (A) /Emotiv (I)
				/Neurosky (N)
				Wearable Sensing (C)

and as the memory load increases, the EEG-informed workload also increases.

2) **Entertainment:** In the consumer application domain, the wireless EEG systems also have a wide range of applications in entertainment, such as gaming, sports, and meditation exercises.

Zao et al. [37] implemented a BCI game played by four people simultaneously. The game was played by EEG activities recorded by Mindo on a smartphone that sent EEG data to a

local FOG server. Abujelala et al. [38] had 15 subjects participating in two different video games while recording changes in their frontal theta activity to assess user engagement; this was achieved by utilizing commercial EEG tools (Muse). Badcock et al. [39] compared the commercial Emotive system against the laboratory-grade Neuroscan system. Their results showed that the Emotiv is comparable to Neuroscan and, consequently, its application can be expected on more occasions in the future.

In contrast to the previous studies, Zink et al. [40] evaluated a smarting mobile EEG system by studying the ERPs and the accuracy of single-trial P300 classification in a three-class auditory oddball paradigm recorded in an outdoor biking scenario. Their results showed that during biking, the P300's reduction was attributed to increased cognitive load. Hashemi, Ali, et al. [41] collected more than 6000 EEG recordings from subjects, ages 18 to 88, during meditation practice via the Muse system, and found changes in EEG power spectra related to age; as age increased, the peak frequency gradually decreased. This study emphasizes the advantages of using large representative samples to address issues related to brain change.

3) Technology: In terms of technology, Xu et al. [3] proposed a review of the development of neurotechnology and its impact on education. For example, wireless EEG systems such as those from NeuroSky Inc. and Emotiv Inc. have been used in education. At present, EEG technology is mainly used in seven areas of education: reading context, interactive behavior, edutainment e-learning, motor skill acquisition, promoting learning performance, and presentation patterns of learning materials. The current technology also encounters two major problems, which are the optimization of experimental design and the inconvenience of wearing an EEG cap for a prolonged period. Abbate et al. [42] showed the usability of wireless EEG devices in fall monitoring systems in a long-term care home for patients with advanced Alzheimer's disease. An ergonomic system was designed to increase the comfort of patients, which reduced sleep disruption and the possibility that patients might take off the EEG cap. Orhan, Umut, et al. [43] proposed a method to utilize rapid serial visual presentation (RSVP) with language models for locked-in syndrome patients. The research team collected EEG responses during random letter observation, a characteristic P300 peak would be detectable in the EEG signals when the desired letter appeared. The results show that this system could achieve an accuracy of about 95% in healthy subjects and 85% in patients. Debener et al. [44] proposed the development of a hidden behind-the-ear electrode array by combining a lightweight mobile EEG amplifier with a mobile phone; the device was designed in a 'C' shape to fit around the ear (cEEGrid) and send signals directly to the mobile phone. The team claimed that the cEEGrid design can collect hours of EEG signals without causing discomfort or interference on subjects' activity, and proved that the device is sufficient to collect ERPs.

4) Communication: In the applications of communication, we have collected several articles related to utilizing wireless EEG systems for controlling robots or brain-machine interfaces (BMI). Kwak et al. [45] used Brain Products EEG devices to develop a lower extremity exoskeleton control system based on SSVEPs and an asynchronous brain-computer interface. The study tested the proposed system on 11 participants and showed that it requires only a small amount of training time to achieve high-quality control of the BMI. Perera et al. [46] highlighted a meal assistant robot that uses SSVEPs to identify user's intentions through EEG signals via an OpenBCI system. The system utilized a combination of camera-based automatic mouth tracking and mouth-opening detection systems, aimed to improve the living convenience of the patient with an

upper limb or spinal cord injury. Stephygraph [47] proposed a Neurosky-based wireless mobile robot control system for individuals with motor disabilities. The robot module reacted to different eye-blink signals to instruct its movement, such as right, left, forward, backward, and stop. Finally, a review paper concerning EEG-based assisted mobile robot control research was published by Krishnan et al. [48], which aimed to recommend EEG technology for patients suffering from various neurological disorders. It compares four different specifications of wireless EEG systems, including headset design, signal preprocessing, feature extraction, and signal classification. Katona et al. [18] used NeuroSky MindWave headsets to record EEG signals from the frontal lobe to control a robot at different speeds; by controlling the speed of the mobile robot, subjects successfully moved the robot to a target position using the frontal EEG signals.

B. Clinical Applications

1) Prevention: EEG signals play an important role in the assessment of sleep physiology. Sterr et al. [49] recorded EEG data during extended nighttime sleep from 20 participants. The sleep data were examined using cEEGrid (Flexible Printed Ear Cap Electrodes Array) and micro-amplifiers combined with the mBrainTrain system and a smartphone. The results showed that the cEEGrid system is a viable recording tool for capturing both sleep and awake EEG. Lin et al. [50] published similar findings, by using the forehead EEG to assess sleep quality and track nighttime sleep patterns. In addition, through dynamic monitoring, the proposed system could alert patients suffering from a sporadic migraine that the symptoms are about to occur.

2) Diagnosis: Another clinical application of wireless EEG systems is in the sphere of diagnosis. As diagnostic applications often require very high precision, conventionally more complex wired EEG devices were used. In 2008, Berger et al. [51] reviewed recent medical rehabilitation historical developments, with a key finding that the development of dry electrodes is a necessity for the future of BCI adoption. More recently O'Sullivan et al. [52] used Cognionics's flexible electrodes and microneedle array electrodes to compare against a gold standard electrode design (Ambu neuroline disposable) for objective testing and subjective evaluation by epilepsy experts. Despite minimal preparation times, their results also showed that the dry electrodes did not degrade the quality of the EEG signals and the waveforms were similar to those recorded by wet electrodes. In 2022, Biondi et al. [22] reviewed the latest clinical and research studies in epilepsy or suspected seizures, which adopted non-invasive mobile EEG systems. They claimed that epileptic patients, technicians, and healthcare providers well tolerated and accepted non-invasive mobile EEG assessments because of their usability and comfort. Collected EEG data from a mobile EEG device is possibly comparable to those collected by conventional EEG systems and can detect EEG abnormalities and seizures visually. They also highlight that mobile EEG equipment could be an important tool for the supplementary diagnosis and management of epileptic patients in a variety of clinical situations. Cao et al. [53] proposed the use of SSVEP-based inherent fuzzy entropy to detect the change of EEG complexity between

the two migraine stages, i.e., interictal (baseline) and pre-ictal (before migraine attacks) phases. Another study was conducted by Alchalabi et al. [54], which used EEG-controlled games to train patients with attention deficit hyperactivity disorder (ADHD), in combination with machine learning algorithms, to detect subjects' attention levels. Another study on ADHD was presented by Wipprecht et al. in 2019. The study mentioned that although ADHD can be controlled by drugs, understanding why children with ADHD are more likely to respond to certain stimuli is limited, therefore Wipprecht introduced a soft and comfortable EEG device equipped with a camera to record the patient's brainwaves and responses [55]

3) Treatment: In the field of clinical treatment, we collected publications discussing adjuvant therapy for depression and neurofeedback. Cao et al. [56] studied the effect of depression treatment using the Mindo system, in which the response to ketamine treatment in patients with treatment-resistant depression (TRD) was explored. The randomized, double-blind, placebo-controlled study provided information on the early changes in the effects of ketamine on patients with TRD. Lee et al. [57] discussed the applications of the Enobio system in medical, neurofeedback, and cognitive-state monitoring.

C. Research Applications

In addition to consumer or clinical applications, wireless EEG systems have also been applied in laboratory research. We have collected publications using wireless EEG systems in basic neuroscience research, signal processing, and signal-quality validation.

1) Neuroscience Research: Numerous neuroscience studies have used wireless EEG headsets, from which we have selected several characteristic and/or representative publications to discuss. Melnik et al. [58] tested four EEG systems: two standard research-level systems, designed as dry-electrode mobile systems, and economical mobile systems, with lower channel counts (ANT Neuro, actiCAP, g.Tec and Emotiv). To determine how variance across systems compares to variance across repeated sessions or subjects. They tested the four devices in six short standard EEG paradigms based on event-related potentials (ERPs) and steady-state visually evoked potential (SSVEP). Placidi et al. [59] proposed using a wireless EEG system for the detection of an aversive smell memory, by a disgusting voluntary brain activation experiment through remembering bad smells.

2) Signal Processing and Comparison: Many researchers have compared the EEG signal quality recorded by different EEG devices and developed signal-processing approaches to remove artifacts, extract informative EEG features, and model the EEG sources for wireless EEG systems. Readers who are interested in the comparison of signal quality between the various devices can read relevant publications.

For real-time modeling, Mullen et al. [60] proposed EEG signal-processing algorithms including data extraction, data preprocessing, pseudo image processing, source reconstruction, and multivariate dynamic systems analysis for Cognionics dry EEG systems. Minguillon et al. [61] reviewed EEG artifact

removal and discussed the applicability to BCIs. They recommended researchers to use a multi-step program and avoid source decomposition filters. Brown et al. [62] discussed the advantages, disadvantages, and features of ABM (B-Alert), EmBand, Emotiv, and Neurosky. Zander et al. [63] evaluated the prototype of the Brain Products three-channel dry-electrode EEG system and compared it to conventional EEG electrode systems. Their results showed that the signal quality of the proposed dry electrodes and the reference conventional wet electrodes have a certain degree of comparability. Specifically, their results showed that at the PO7 channel, average power spectral densities and alpha power of the proposed dry electrodes and the reference conventional wet electrodes have no significant difference. Hairston et al. [64] compared ABM(B-Alert), DSI, Emotiv, and Biosmei (a widely used wired device). The wired device served as a benchmark to evaluate the adaptability of the other three wireless devices to different head sizes, subject preferences, and electrical connection stability. In addition, Radüntz [65] reviewed the signal quality of six different EEG devices and showed that the signal quality of gel-based and non-gel devices did not differ greatly. Di Flumeri et al. [66] evaluated three types of electrodes, including active dry gold (BP-Gold), hybrid dry multi-spikes (DSI), and passive-dry solid-gel electrodes (BP-solid), in terms of signal spectral features, mental state classification, and usability. The results showed that dry electrodes could match high standards, compared to wet electrodes, but with enhanced comfort. Estep et al. [67] showed that there is a good correlation in signals recorded using both dry and wet electrodes from the frontal lobe of different hair types. However, the correlation between wet and dry electrodes is significantly lower than that between two wet DSI electrodes.

D. Summary of Exemplar Publications Applying Wireless EEG Systems

Table II lists the publications involving various wireless EEG systems in the three main fields. Of the 44 articles in Table II, 24 articles (54%) were categorized as consumer applications, ten articles (23%) were grouped as clinical applications and 10 articles (23%) showed applications in research applications. The sample papers presenting wireless EEG systems for consumer applications account for the largest proportion, indicating that wireless devices were mostly applied in consumer or real-world environments. According to the years of collected sample publications, the number of articles published in various application fields in the last five years is higher than the number of articles published over five years ago. There appears to be an increasing trend of wireless EEG systems research in every application area, especially in the recent five years from which most of this selection was drawn. The development and application of wireless EEG systems are expanding rapidly.

The research coverage of newly marketed devices was limited. Therefore, not every wireless EEG system is present in Table II. Table III is created based on the keywords and contents of the publications listed in Table II. Table III lists all of the applications that have been published, along with several recently released products that would be suitable for similar applications in each

TABLE III
SUMMARY OF PUBLISHED APPLICATIONS

	Consumer	Clinical	Research
Used systems	B-Alert X-24, Quick-30, LiveAmp, g.Tec, Smarting, Enobio, LooxidVR, EPOC ^x , The All-in-One Electrode Cap Kit, Mindo, MindWave Mobile 2, Muse2.	Cognionics Wearable Sensing g.Tec, mBrainTrain, Neuroelectrics, Emotiv, Unicorn Brain Interface, Mindo	B-Alert X-24, Cognionics, Wearable Sensing, Brain Products, g.Tec, mBrainTrain, Neuroelectrics, Emotiv, Mindo NeuroSky
Similar systems	Wearable Sensing, Artise, Unicorn Brain Interface, Mindrove	B-Alert X-24 Brain Products	Artise, OpenBCI, Unicorn Brain Interface, Mindrove



Fig. 4. Example of monitoring sleep quality in a home environment by using a wireless EEG system. The participant wore a portable headband system with five electrodes, which can continuously track the quality of sleep for 8-10 hours [68]. The electrodes of this device are placed on the forehead and are wireless, so the experiment will not be affected by whether the subject is lying flat or sideways.

category. A wide range of devices could be adopted for consumer applications. Price and convenience are crucial factors. Features such as low cost and low density could potentially attract more users, depending on the specific use cases. FDA or CE-certified EEG systems such as [A] and [D] could potentially be used in clinical settings. Devices such as [J], [K], [L], and [O] provide access to raw EEG data, the availability of which is of great importance for research application. The details will be discussed in the next section.

V. HOW TO CHOOSE A SUITABLE WIRELESS EEG SYSTEMS ?

According to the previous comparison (see Part III) of the basic performance parameters of wireless EEG systems and the survey on how predecessors have used wireless devices within different fields (see Part IV), there is a wide variety of devices that could be adopted by users. To address this multitude of options, this survey examines some scenarios for finding a suitable device, the vital selection criteria needed to combine personal requirements with actual application conditions, and examples of possible options that could be chosen. The following sections illustrate how such device selection might occur across the different categories of applications for which wireless EEG systems can be used, such as consumption-based entertainment and real-time physiological monitoring, the prevention, diagnosis, and auxiliary treatment under clinical applications, and basic EEG-based neuroscience research.

A. Wireless EEG Systems for Consumer Application Selection

Wireless EEG systems are developing at an unprecedented speed in the consumer market, with most devices focusing on applications in health care, education, or entertainment. These wireless EEG systems can be used to meditate, self-monitor their own physiological state, play games, and engage in other relaxation or entertainment activities. To use EEG for these activities at home or in daily life, low price, dry electrode, light, portable, low-density, fast setup wireless EEG systems are more in line with the needs of consumers. For example, if you want

to assess your sleep quality at home, as shown in Fig. 4, a low-density wireless device is more convenient and flexible than a high-density wireless device used in clinical sleep studies.

A study on observing sleep fluctuations in the home environment used a low-density EEG system (Actiwave, CamNtech Ltd England) with six dry electrodes [69]. The first part of the study used a wireless EEG system to collect EEG signals from 20 young subjects. After analyzing the EEG signal and comparing it with a polysomnogram (PSG), the Pearson correlation between the wireless device and PSG signal reached 0.6. Their time-frequency relationship showed that the frequency distribution of the two was very similar throughout the night. The second part collected 90 middle-aged subjects who received closed-loop auditory stimulation over one or 10 nights. The results showed that the wireless device could automatically detect N3 sleep in real-time and accurately send auditory stimulation during slow oscillation sleep.

Using EEG as a direct control apparatus to play game receives increasing attention recently. Zhanget al. [70] designed SSVEP games under different time pressure. There is also a game system that combines VR equipment with SSVEP [71], which utilized a low-density Emotiv EPOC^x EEG system with 14 channels, 14-bit ADC, and 128 Hz sampling frequency. The system used flashing SSVEP signals displayed in a VR helmet and VR's immersive first-person visual feedback to pilot a helicopter in 3D navigation. The results indicate that the subjects were able to direct the quadcopter to the designated area within 3 minutes, with an average control accuracy reached 83.3%.

B. Wireless EEG Systems for Clinical Application Selection

The most common application of EEG technology is in clinical fields [72]. EEG-based clinical research is used to investigate ameliorative treatments and evaluation of preventative frameworks. In terms of assist treatment and rehabilitation conditional, to produce the necessary signal reliability, medium or high-density FDA or CE-certified wireless EEG systems are appropriately suited. For example, a CE-certified Enobio EEG system, a medium-density wireless device, was used in an



Fig. 5. Practical example of extra-skeletal assisted rehabilitation using a wireless EEG system to monitor brain activity. The system combines a wireless headset with three electrodes and a lower limb rehabilitation robot. The participant used the system to record the changes in lower limb movement and EEG data during the rehabilitation process, and assisted the physician to evaluate the rehabilitation efficacy.

arm-assisted rehabilitation study [73]. The study used low-cost robots and motor imagery to improve arm-assisted rehabilitation. The first goal was to verify the safety of the MI-BCI for the control of a robot by healthy subjects. The second goal was to determine which MI strategies are better for controlling different rehabilitation apparatuses. Experimental results showed that the subjects could use intention via MI-EEG to control the robotic system and all healthy subjects could perform the expected arm movements. In addition, wireless EEG systems can also be incorporated with active exoskeletal-assisted rehabilitation training to monitor central nervous system (CNS) activity. If a patient has to stay in bed, placing electrodes over the occipital areas is difficult. Then, a low-density EEG headset with sensors placed over the central areas is more feasible and suitable in this application, as shown in Fig. 5. Real-time monitoring of CNS activity is crucial for evaluating the acute restoration and enhancement of motor-related brain function after stroke.

In terms of applications for preventive diagnoses, such as the prediction of migraines or the diagnosis of ADHD in children, minimal- to no-preparation time and ease to cleanup are preferred. Therefore, users will tend to use low-density wireless EEG systems with dry electrodes. Migraine attacks can cause nausea, vomiting, and/or sensitivity to light, sound, and/or movement, which makes it inconvenient to measure EEG signals with the traditional wired systems with wet/gel electrodes or other devices with long preparation times. Therefore, low-density wireless EEG systems with dry electrodes can be used for migraine prediction or related research. For example, a low-density (4-channel) Mindo EEG system was utilized in a prevention of migraine study [53], which proposed a new application of multi-scale relative inherent fuzzy entropy that used repetitive steady-state visual evoked potentials (SSVEP) to analyze EEG changes before and during migraine attacks. They used six machine learning classification methods for binary classification of migraine onset and pre-onset. Empirical results showed that inherent fuzzy entropy provides novel applications with appropriate visual stimuli, the resulting accuracy of AdaBoost ensemble classification was as high as 81%, and these



Fig. 6. Example of research by Djebbara et al. [74]. The participants wore a VR head-mounted display (windows mixed reality) on a 64-channel EEG system (eegoSports, ANT Neuro) to study the relationship between cognitive and physical movement.

techniques are a promising hope for early migraine warning systems.

C. Wireless EEG Systems for Research Application

Laboratory research is still one of the major application areas for wireless EEG systems. To push the knowledge boundaries of basic neuroscience, EEG recorded with high spatial resolution and high signal quality is preferred to pinpoint precise brain activity. Therefore, high-density gel-based wireless EEG systems with high sampling rates and good resolutions are most suitable. Research in neural engineering mainly revolves around the development of BCI systems for applied applications. This research domain's primary interests include system preparation time and users' comfort. Researchers of neural engineering therefore tend to favor medium density wireless EEG systems with dry electrodes. The system cost is also a deciding factor to improve future applicability to public domains.

A high-density ANT Neuro eegoSports EEG system with 64 channels, 24-bit resolution, and sampling frequency of 500 Hz was utilized in a mobile brain/body imaging study [74], as shown in Fig. 6. This basic neuroscience study used virtual reality to investigate the relationship between cognition and physical movement. The results showed the activation of sensory-related brain areas on the revelation of a virtual environment, preceding any actual movement. This study provides new neurological evidence for the action-perception mode of cognition. The Emotiv EPOC^X is a medium density EEG system with 16 electrodes and a sampling frequency of 128 Hz. This system has found its way into neural engineering research on emotion recognition. DREAMER, a publicly available dataset recorded during audio-visual emotion elicitation studies utilized an Emotiv EPOC^X for EEG data acquisition [75]. According to the article, Emotiv EPOC^X was selected due to its properties such as portable, wearable, wireless, low-cost, and off-the-shelf, which would allow for everyday applications. The classification of emotional states using such a medium density system was found to be comparable to EEG datasets acquired from non-portable, costly, medical grade devices.

VI. DISCUSSIONS AND CONCLUSION

Recently, increased attention has been focused on the variety of wireless EEG systems, with many companies having invested in relevant research, from electrode development/selection to hardware integration and software platforms. As mentioned in the introduction, non-invasive wireless EEG systems are relatively more convenient because they are easy to use with quick set up time compared to wired EEG systems. They are more suitable for real-world applications [25] because they could be used outside the laboratory to monitor the brain activity of unconstrained individuals in real life. Studies have shown that signals acquired by several wireless EEG systems have comparable quality with those recorded using wired EEG technology [57], [76], including a study that showed Advanced Brain Monitoring (ABM) systems are comparable to wired BioSemi EEG systems, in terms of signal quality and frequency power [77].

This study surveyed and highlighted the trends in wearable and wireless EEG systems over the past decade. Publication of articles on wireless EEG trends indicated that wireless EEG systems could be more accessible to researchers, academics and companies have started to recognize the potential of wireless EEG systems, and researchers have shifted more efforts to implement wireless EEG for practical applications. This study conducted a large-scale review of the specifications of 16 selected wireless EEG systems, such as system cost, sensor types, sensor cost, number of channels, sampling rate, battery life, the year of announcement, certification, and product link. This large-scale comparison list can provide researchers with a direct reading guide when choosing an EEG device in the future. Additionally, we provide a list of devices that were released in 2022 or will be available in 2023 for people to choose from, such as BrainBit, Mindtooth Touch, BrainProducts X.on, Neurosity Crown, and Melamine.

Moreover, this article provides a comprehensive reference for wireless EEG systems for a variety of applications. Such a review of the literature describing or proposing applications of wireless EEG systems, when combined with the overview of features, cost-effectiveness, functions, and impact of these systems on existing research provides readers an overview for incorporating wireless EEG systems into a variety of situations. Furthermore, this paper also discusses the suitability of devices in terms of personalization and use cases specificities. Combining the above literature application survey and personal needs, we summarize the application conditions of wireless EEG systems: 1) Low price, dry electrodes, light weight, portability, low density, and easy setup are important factors for consumer applications; 2) Wireless EEG systems with FDA or CE marking are important for use in a clinical setting; 3) Wireless EEG systems that can provide raw EEG data and high-density channels are important for research application. This review is intended to provide an overview of the current state of the field, with the expectation that it will provide a baseline reference as more influential and novel research is conducted, both to promote and benefit from the development and widespread use of wireless EEG systems.

Our literature review reveals a rapid emergence of non-invasive wireless EEG systems focused on various applications.

Despite promising results, the adoption of these technologies into clinical practice needs to be improved. A few of the limitations of wireless EEG systems that could be hindering their wide usage in clinical settings include interference of wireless transmission between various clinical devices, information security of patient data, and relatively short battery life [78]. Future studies should focus on assessing such systems' accuracy, feasibility, and acceptability in a range of settings. The evidence available is promising, and the new non-invasive mobile EEG has a strong potential to become clinically valuable for managing people with brain-related disorders in and outside the hospital.

APPENDIX

	Wireless EEG systems	Link
[A]	AdvancedBrainMonitoring /B-Alert X-24	https://www.advancedbrainmonitoring.com/xseries/
[B]	Cognionics /Quick-30	https://www.cognionics.net/us-price
[C]	Wearable sensing/DSI-24	https://wearablesensing.com/products/dsi-24/
[D]	Brain Products/ LiveAmp	https://www.brainproducts.com/productdetails.php?id=63&tab=2
[E]	g. Tec /g. Nautilus pro with g. SAHARA	https://www.gtec.at/product/gnautilus-pro/
[F]	mBrainTrain/Smartering	https://mbraintrain.com/smartering/
[G]	Neuroelectrics /Enobio	https://www.neuroelectrics.com/products/enobio/
[H]	LooxidVR Labs/ LooxidVR	https://looxidlabs.com/looxidvr/
[I]	Emotiv /EPOC ^x	https://www.emotiv.com/
[J]	Artise/ Altaire	http://www.artisebio.com/altaire/
[K]	OpenBCI/ All-in-One EEG Electrode Cap Starter Kit	https://reurl.cc/GxALYA
[L]	Unicorn brain interface /Unicorn hybrid black	https://reurl.cc/RrzEo9
[M]	Mindo/ BR8	http://mindoc.com.tw/tw/goods.php?catId=1
[N]	NeuroSky/MindWave Mobile 2	https://store.neurosky.com/pages/mindwave
[O]	Mindrove	https://mindrove.com/
[P]	InteraXon /Muse2	https://choosemuse.com/muse-2/
[Q]	Imec/ EEG headset platform	https://www.imec-int.com/en/eeeg
[R]	Zeto/Zeto	https://zeto-inc.com/device/
[S]	Ant Neuro/Eego sports	https://www.ant-neuro.com/products/eego_sports

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