Evaluation of the Effectiveness of a Wearable, {AR}-based {BCI} for Robot Control in {ADHD} Treatment

(Article begins on next page)

Evaluation of the Effectiveness of a Wearable, AR-based BCI for Robot Control in ADHD Treatment

Pasquale Arpaia
Interdepartmental Research Center in Health Management and Innovation in healthcare
University of Naples Federico II
Naples, Italy

Sabatina Criscuolo
Department of Information Technology and Electrical Engineering
University of Naples Federico II
Naples, Italy

Egidio De Benedetto
Department of Information Technology and Electrical Engineering
University of Naples Federico II
Naples, Italy
egidio.debenedetto@unina.it

Nicola Donato
Department of Engineering
University of Messina
Messina, Italy

Luigi Duraccio
Department of Electronics and Telecommunications
Polytechnic University of Turin
Turin, Italy

***Abstract*—A highly wearable, single-channel Brain-Computer Interface based on Augmented Reality and Steady-State Visually Evoked Potentials is proposed as a therapy for Attention Deficit Hyperactivity Disorder (ADHD) rehabilitation of children. Through the proposed system, the user can drive a *social robot*, in real-time, by simply looking at the flickering icons rendered on the Augmented Reality (AR) smart glasses. The *social robot* is already successfully employed for ADHD treatment.**

After a preliminary evaluation of the children adherence to the therapy (involving 18 subjects), a one-month therapy was conducted on 7 participants. During the tests, different tasks were assigned to the children depending on their level of involvement. The obtained results, based on the Italian Battery for ADHD, highlight that for all the participants, an improvement in the various tests proposed could be observed, even with a low number of sessions.

***Index Terms*—ADHD Therapies, Augmented Reality, Brain-Computer Interfaces, Health 4.0, Robot-Assisted Therapies, Wearable Systems**

I. INTRODUCTION

The *Health 4.0* paradigm is the natural extension of *Industry 4.0* to the medical sector [1], [2]. Indeed, the enabling technologies derived from the Fourth Industrial Revolution - i.e., Artificial Intelligence [3], Cloud Computing [4], Machine and Deep Learning [5], wearables and Internet of Things [6], [7], Augmented Reality [8]–[13], Soft growing robots [14]–[16] - have a high potential in various fields, in particular in healthcare. These technologies allow to virtualize and enable new processes related to healthcare, and turn them into services [17]. Among the actions necessary for the digital transition in the medical field, the redefinition of the patient care and the better patient alignment to the various specific clinical situations have gained momentum, favoring a *patient-centered* approach, which means to provide the patient with personalized services that adapt to his/her needs, and not vice-versa. This approach is intended to guarantee comfort, and easy of use to the service, improving, at the same time, the efficiency.

Among the enabling technologies that contribute to favoring digital transformation of healthcare, Augmented Reality (AR) allows easier access for the fruition of virtual information. Currently, this technology is successfully employed in a very wide scenarios, for example (i) helping the medical team during surgical interventions [18], [19], (ii) monitoring the patient health status [20], or (iii) in rehabilitation [21].

Another technology that is contributing to the digital transformation of the healthcare is certainly represented by the Brain-Computer Interfaces (BCIs). BCIs are an integration of hardware and software which aims to create a *virtually-direct* path between the human brain and external devices: depending on the BCI paradigm, a user's intention can be translated into specific commands [22], [23]. Among the BCI major paradigms, Steady-State Visually Evoked Potentials (SSVEPs) are successfully used in several healthcare applications [24], [25]. Typically, SSVEPs are brain signals characterized by a sinusoidal-like waveform having a fundamental frequency equal to that of the observed flickering stimulus. Often, higher harmonics can also be detected [26]. Therefore, in SSVEP-based applications, N flickering stimuli at different frequencies are associated to specific commands, so that the user can select the desired target by simply looking at the corresponding stimulus [27].

In this work, a combined fully-wearable AR/BCI system was used for the remote control of a robot in *attention deficit/hyperactivity disorder (ADHD)* rehabilitation pediatric therapies [28]. In this system, the AR becomes a new input for the BCI: the smart glasses generate the flickering stimuli

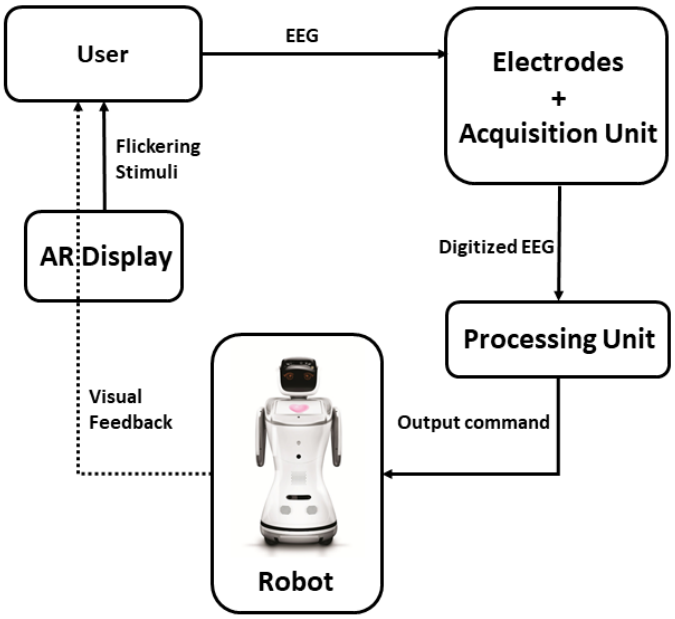


Fig. 1. System architecture.

which elicit the user's SSVEP, which is acquired by electrodes placed on the user's scalp [29]. In this way, the patient can move a robot to the left or to the right by simply looking at the corresponding flickering icon. Moreover, the patient can use eye-blining to make the robot go forward or stop. This enhances patient engagement and therefore the effectiveness of the therapy, allowed to effectively treat the typical symptoms of ADHD, such as inattention, hyperactivity, impulsiveness [30].

After a preliminary evaluation of the children adherence to the therapy involving 18 subjects [31], a one-month therapy was conducted on 7 participants. During this period, different tasks were assigned to the children depending on their level of involvement. The experimental results, based on the Italian Battery for ADHD (BIA) [32], showed encouraging outcomes. In fact, all the participants observed an improvement in the various test proposed, even with a low number of sessions.

The paper is organized as follows. Section II describes the system architecture, along with the hardware employed and the description of the therapy. The experimental results are shown in Section III and, finally, conclusions are drawn in Section IV.

II. Materials and Methods

A. System Architecture

The architecture of the BCI instrumentation is shown in Fig. 1. An *AR Display* renders 2 flickering stimuli to elicit users SSVEPs. Then, three dry *Electrodes* are placed in *Oz*, *Fz*, and *A2* positions, according to the 10-20 International System [28], and capture the user EEG. The electrodes are connected to a portable *Acquisition Unit*, which sends the digitized EEG samples to a portable *Processing Unit*. The processing unit runs the SSVEP/eye-blink classification algorithm, and sends in real time the output command to the *Robot*, which actuates the command associated to the stimulus the user gazed, also providing a visual feedback to the user.

The wearability and portability of the system is guaranteed by the use of (i) a single-channel electroencephalografic (EEG) acquisition, (ii) dry electrodes, and (iii) a training-less signal processing strategy. The use of AR also allows the patients to simultaneously watch the stimuli and the robot, which provides feedback both in terms of movement and speech.

B. Hardware

The adopted hardware is described below.

- *AR Display*: Epson Moverio BT-200. These Glasses are equipped with Android OS 4.0.4 and have a 60 Hz Refresh Rate, with a 23° diagonal field of view. It represents a good compromise between performance and cost, with respect to other, more expensive AR devices like Microsoft Hololens 2.
- *Acquisition Unit*: Olimex EEG-SMT, a 10-bit, 256 S/s, open source Analog-to-Digital converter.
- *Processing Unit*: Raspberry Pi 4, a single-board PC connected via USB to the Acquisition Unit.
- *Robot*: The robot chosen for this application was a SanBot Elf [28], [31], a humanoid robot developed and produced by Qihan Technology Co. It receives in real-time the commands from the Processing Unit and actuates them.

C. Software

The Software implemented on the device is described as follows.

- *AR Display*: The AR environment was realized by developing an Android application with Android Studio. It consists in two arrows placed at the edges of the screen and flickering at 10 Hz and 12 Hz, respectively.
- *Processing Unit*: A Software written in C acquires the signal coming from the Acquisition Unit over UART protocol and runs the SSVEP/eye-blink classification algorithm. Then, it sends the output command to the Robot via TCP/IP.
- *Robot*: An Android application was developed to receive via TCP/IP the commands coming from the Processing Unit and actuate them in real time.

D. Operation

The user wears the AR-BCI equipment and starts the Android application on the AR glasses. In this way, the two flickering stimuli to drive the robot are displayed as shown in Fig. 2. The user, keeping their focus on the desired arrow, makes the system move the robot to the left or to the right. Then, by an eye-blink, the robot moves forward until a further eye-blink stops it [28].

TABLE I
RESULTS OF THE BIA TEST ON THE SEVEN PARTICIPANTS

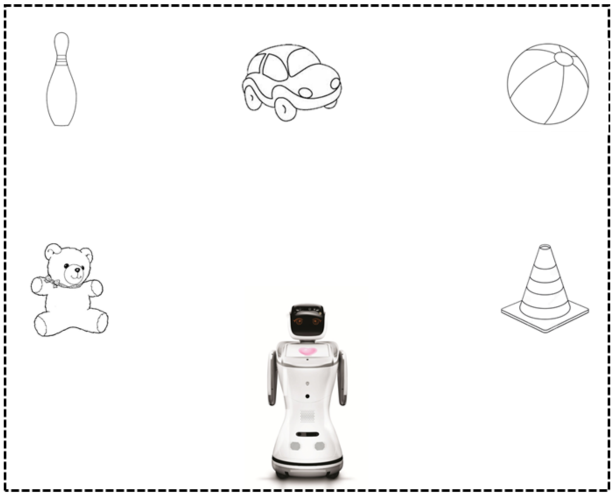
	Semantic fluency	Phonological fluency	Visual-sequential	Span-4	Reading	”Ranette” test	Tau
· Subject #1 - 7 years old; performance deficit: inattention, severely premature.							
Initial Evaluation	25 words/min	0 words/min	28/32	5	1 error	14/20	8/10
Intermediate Evaluation	25 words/min	2 words/min	28/32	5	0 errors	15/20	8/10
Final Evaluation	27 words/min	3 words/min	28/32	5	0 errors	16/20	8/10
· Subject #2 - 10 years old; performance deficit: immaturity, psycho-emotional deficit.							
Initial Evaluation	26 words/min	8 words/min	31/32	3	0 errors	14/20	9/10
Intermediate Evaluation	26 words/min	9 words/min	32/32	3	0 errors	14/20	10/10
Final Evaluation	27 words/min	10 words/min	32/32	3	0 errors	15/20	10/10
· Subject #3 - 9 years old; learning disability.							
Initial Evaluation	28 words/min	10 words/min	24/32	4	1 error	3/20	8/10
Intermediate Evaluation	33 words/min	7 words/min	30/32	4	0 errors	5/20	10/10
Final Evaluation	34 words/min	8 words/min	30/32	4	0 errors	5/20	10/10
· Subject #4 - 10 years old; psycho-motor development disorder, attention disorder.							
Initial Evaluation	35 words/min	25 words/min	32/32	4	0 errors	18/20	10/10
Intermediate Evaluation	36 words/min	28 words/min	32/32	4	0 errors	18/20	10/10
Final Evaluation	40 words/min	28 words/min	32/32	4	0 errors	18/20	10/10
· Subject #5 - 10 years old; behavior disorder							
Initial Evaluation	35 words/min	13 words/min	20/32	3	1 error	6/20	4/10
Intermediate Evaluation	36 words/min	15 words/min	21/32	3	0 errors	6/20	5/10
Final Evaluation	40 words/min	15 words/min	23/32	3	0 errors	10/20	5/10
· Subject #6 - 9 years old; generalized anxiety disorder.							
Initial Evaluation	38 words/min	15 words/min	32/32	4	0 errors	16/20	8/10
Intermediate Evaluation	40 words/min	16 words/min	32/32	4	0 errors	16/20	9/10
Final Evaluation	40 words/min	18 words/min	32/32	4	0 errors	17/20	9/10
· Subject #7 - 8 years old; visual-spatial motor difficulty, communication disorder, attention disorder.							
Initial Evaluation	16 words/min	4 words/min	30/32	3	0 errors	10/20	8/10
Intermediate Evaluation	16 words/min	4 words/min	30/32	3	0 errors	12/20	8/10
Final Evaluation	17 words/min	5 words/min	31/32	3	0 errors	12/20	8/10

Fig. 2. User’s view during the task. The two arrows flicker at different frequency values.

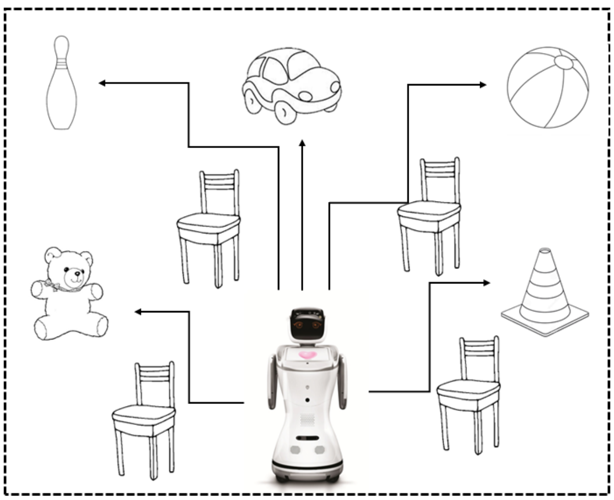
E. Therapy Description

The therapy, which was conceived by experienced therapists, is divided into four tasks. More specifically, the first task (*Task 0*) is aimed to evaluate the children adherence to therapy, while the remaining three tasks are addressed to the therapy administration for the selected children.

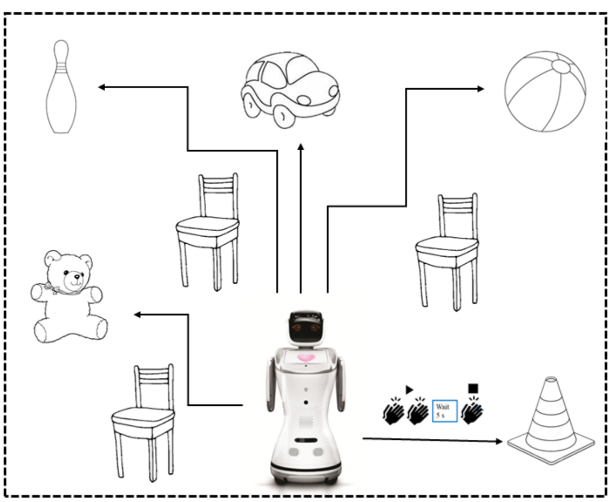
- *Task 0*: First, the user is asked to wear the BCI-AR equipment. In this way, possible initial reluctance is immediately verified. If the user decides to continue and use the system, he/she is left free to move the Robot at will. Therefore, during the task, his/her capability to use the system, and his/her reactions to mistakes is monitored. In this way, the children adherence to the therapy was completely determined on 18 subjects. Then, the most suitable candidates were selected for the successive tasks.
- *Task 1*: Task 1 involves the arrangement of a number of objects in different points of the space. Then, the children is asked to freely choose the path to make the robot reach the object indicated by the therapist, without communicating it. During the task, it is checked whether the child is able to move the Robot following a logical path or in a disordered way. Figure 3(a) shows a sketch of an example of the objects placement in the room.
- *Task 2*: The difficulty increases with the Task 2, since a number of obstacles (i.e. chairs) are added between the Robot and the objects to reach. A sheet of paper is shown to the child, and he/she is asked to draw the path which, according to him, represents the best solution to reach the object indicated by the therapist. In this way, his/her planning and problem-solving skills can be stimulated. During the task, the child’s ability and consistency in (i) mentally planning the trajectory, (ii) verbalizing it, and (iii) making the Robot execute it, is monitored. Figure 3(b) shows an example of the obstacle arrangement in the room with an example of trajectory (a) and the patient’s view (b).



(a)



(b)



(c)

Fig. 3. Sketch of the disposition of objects during the different tasks: (a) task #1; (b) task #2; (c) task #3.

- *Task 3*: Task 3 is characterized by the introduction of an external input provided by the therapist. More specifically, during the execution of the task, the child must be attentive to the reception of sounds (such as an hands' clap), which indicate that he/she has to start/stop the Robot movements. In this way, the performance in terms of hyperactivity and attention is monitored at an higher stage. In fact, the child is stimulated (i) to be ready to receive external inputs, and (ii) to keep the attention high to perform the task. Figure 3(c) shows how the objects arranged in the space with an example of external input during the execution of the trial.

III. Results

Seven different tests, based on the Italian Battery for ADHD (BIA), were administered to the children, namely *Semantic fluency, Phonological fluency, Visual-sequential, Span-4, Reading, "Ranette" test, and Tau*.
The children participated in the experiments only once a week for one month. Three evaluations were conducted: at the start of the sessions (day #0), at mid-trial (day #15), and at the end of the therapy (day #30).
The results obtained applying the proposed therapy on seven children are summarized in Table I. Overall, it is possible to observe an improvement in the various tests proposed. Therefore, the level of attention has boosted even with a low number of sessions. The positive results obtained in this pilot study offer a starting point for a more in-depth evaluation of the efficacy of the proposed therapy over a longer period.

IV. Conclusion

A system, integrating AR glasses with a non-invasive Brain Computer Interface based on SSVEP, is proposed in rehabilitation therapies for ADHD children. An untrained user can move a robot by focusing flickering stimuli and using eye-blinking. The system manages to overcome the main challenges posed today by the use of innovative strategies for the rehabilitation of children with ADHD. These challenges are related to acceptability and degree of involvement guaranteed by the proposed therapeutic setups. A clinical ADHD case study at an accredited rehabilitation center centering on 18 patients showed positive feedback regarding device acceptance and adherence to therapy. Overall, the children were enthusiastic to pilot the robot and agreed to wear the AR electrodes and glasses. A preliminary study at the same accredited rehabilitation center on 7 ADHD children involved in a one-month therapy with the proposed system showed an increase in their attentional performance. Based on the encouraging results obtained so far, future work will be carried out (i) extending the number of patients involved and considering a longer therapy period, and (ii) including an additional number of flickering stimuli in order to allow a wider range of selection to the user.

Acknowledgment

The Authors would like to thank Villa delle Ginestre for the support in the experimentation.

REFERENCES

[1] H. Qiu, M. Qiu, M. Liu, and G. Memmi, "Secure health data sharing for medical cyber-physical systems for the healthcare 4.0," *IEEE Journal of Biomedical and Health Informatics*, vol. 24, no. 9, pp. 2499–2505, 2020.

[2] P. D'Amore and A. Tedesco, "Technologies for the implementation of a security system on rail transportation infrastructures," *Topics in Safety, Risk, Reliability and Quality*, vol. 27, pp. 123–141, 2015.

[3] B. Alotaibi, "Utilizing blockchain to overcome cyber security concerns in the internet of things: A review," *IEEE Sensors Journal*, vol. 19, no. 23, pp. 10953–10971, 2019.

[4] P. Pace, G. Aloi, R. Gravina, G. Caliciuri, G. Fortino, and A. Liotta, "An edge-based architecture to support efficient applications for healthcare industry 4.0," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 1, pp. 481–489, 2019.

[5] A. Apicella, P. Arpaia, E. De Benedetto, N. Donato, L. Duraccio, S. Giugliano, and R. Prevete, "Enhancement of SSVEPs classification in BCI-based wearable instrumentation through machine learning techniques," *IEEE Sensors Journal*, pp. 1–1, 2022.

[6] R. Schiavoni, G. Monti, E. Piuzzi, L. Tarricone, A. Tedesco, E. De Benedetto, and A. Cataldo, "Feasibility of a wearable reflectometric system for sensing skin hydration," *Sensors*, vol. 20, no. 10, 2020.

[7] L. Corchia, G. Monti, E. De Benedetto, A. Cataldo, L. Angrisani, P. Arpaia, and L. Tarricone, "Fully-textile, wearable chipless tags for identification and tracking applications," *Sensors*, vol. 20, no. 2, 2020.

[8] P. Arpaia, D. Dallet, E. Erra, and A. Tedesco, "Reliability measurements of an augmented reality-based 4.0 system for supporting workmen in handmade assembly," in *24th IMEKO TC4 International Symposium and 22nd International Workshop on ADC and DAC Modelling and Testing*, pp. 190–195, 2020.

[9] P. Arpaia, E. De Benedetto, and L. Duraccio, "Design, implementation, and metrological characterization of a wearable, integrated ar-bci hands-free system for health 4.0 monitoring," *Measurement*, vol. 177, p. 109280, 2021.

[10] F. Cutolo, B. Fida, N. Cattari, and V. Ferrari, "Software framework for customized augmented reality headsets in medicine," *IEEE Access*, vol. 8, pp. 706–720, 2020.

[11] G. Badiali, V. Ferrari, F. Cutolo, C. Freschi, D. Caramella, A. Bianchi, and C. Marchetti, "Augmented reality as an aid in maxillofacial surgery: validation of a wearable system allowing maxillary repositioning," *Journal of cranio-Maxillofacial surgery*, vol. 42, no. 8, pp. 1970–1976, 2014.

[12] A. Meola, F. Cutolo, M. Carbone, F. Cagnazzo, M. Ferrari, and V. Ferrari, "Augmented reality in neurosurgery: a systematic review," *Neurosurgical review*, vol. 40, no. 4, pp. 537–548, 2017.

[13] S. Condino, G. Turini, P. D. Parchi, R. M. Viglialoro, N. Piolanti, M. Gesi, M. Ferrari, and V. Ferrari, "How to build a patient-specific hybrid simulator for orthopaedic open surgery: benefits and limits of mixed-reality using the microsoft hololens," *Journal of healthcare engineering*, vol. 2018, 2018.

[14] L. Angrisani, S. Grazioso, G. Di Gironimo, D. Panariello, and A. Tedesco, "On the use of soft continuum robots for remote measurement tasks in constrained environments: a brief overview of applications," in *2019 IEEE International Symposium on Measurements & Networking (M&N)*, pp. 1–5, IEEE, 2019.

[15] S. Grazioso, A. Tedesco, M. Selvaggio, S. Debei, and S. Chiodini, "Towards the development of a cyber-physical measurement system (CPMS): Case study of a bioinspired soft growing robot for remote measurement and monitoring applications," *ACTA IMEKO*, vol. 10, no. 2, pp. 104–110, 2021.

[16] S. Grazioso, A. Tedesco, M. Selvaggio, S. Debei, S. Chiodini, E. De Benedetto, G. Di Gironimo, and A. Lanzotti, "Design of a soft growing robot as a practical example of cyber–physical measurement systems," in *2021 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4. 0&IoT)*, pp. 23–26, IEEE, 2021.

[17] A. Khelassi, V. V. Estrela, A. C. B. Monteiro, R. P. França, Y. Iano, N. Razmjooy, *et al.*, "Health 4.0: applications, management, technologies and review," *Medical Technologies Journal*, 2019.

[18] S. Condino, N. Montemurro, N. Cattari, R. D'Amato, U. Thomale, V. Ferrari, and F. Cutolo, "Evaluation of a wearable AR platform for guiding complex craniotomies in neurosurgery," *Annals of Biomedical Engineering*, 2021.

[19] P. Arpaia, E. De Benedetto, C. A. Dodaro, L. Duraccio, and G. Servillo, "Metrology-based design of a wearable augmented reality system for monitoring patient's vitals in real time," *IEEE Sensors Journal*, vol. 21, no. 9, pp. 11176–11183, 2021.

[20] P. M. Sanderson, M. O. Watson, W. J. Russell, S. Jenkins, D. Liu, N. Green, K. Llewelyn, P. Cole, V. Shek, and S. S. Krupenia, "Advanced auditory displays and head-mounted displays: advantages and disadvantages for monitoring by the distracted anesthesiologist," *Anesthesia & Analgesia*, vol. 106, no. 6, pp. 1787–1797, 2008.

[21] A. Alamri, J. Cha, and A. El Saddik, "Ar-rehab: An augmented reality framework for poststroke-patient rehabilitation," *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 10, pp. 2554–2563, 2010.

[22] J. R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T. M. Vaughan, "Brain–computer interfaces for communication and control," *Clinical neurophysiology*, vol. 113, no. 6, pp. 767–791, 2002.

[23] A. Tedesco, D. Dallet, and P. Arpaia, "Augmented reality (AR) and brain-computer interface (BCI): Two enabling technologies for empowering the fruition of sensor data in the 4.0 era," *Lecture Notes in Electrical Engineering*, vol. 753, pp. 85–91, 2021.

[24] P. Arpaia, E. De Benedetto, and L. Duraccio, "Design, implementation, and metrological characterization of a wearable, integrated AR-BCI hands-free system for health 4.0 monitoring," *Measurement*, vol. 177, 2021.

[25] X. Zeng, G. Zhu, L. Yue, M. Zhang, and S. Xie, "A feasibility study of ssvep-based passive training on an ankle rehabilitation robot," *Journal of healthcare engineering*, vol. 2017, 2017.

[26] G. R. Müller-Putz, R. Scherer, C. Brauneis, and G. Pfurtscheller, "Steady-state visual evoked potential (SSVEP)-based communication: impact of harmonic frequency components," *Journal of neural engineering*, vol. 2, no. 4, p. 123, 2005.

[27] L. Angrisani, P. Arpaia, A. Esposito, and N. Moccaldi, "A wearable brain-computer interface instrument for augmented reality-based inspection in industry 4.0," *IEEE Transactions on Instrumentation and Measurement*, 2019.

[28] P. Arpaia, L. Duraccio, N. Moccaldi, and S. Rossi, "Wearable brain-computer interface instrumentation for robot-based rehabilitation by augmented reality," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 9, 2020.

[29] P. Arpaia, E. De Benedetto, L. De Paolis, G. D'Errico, N. Donato, and L. Duraccio, "Performance enhancement of wearable instrumentation for ar-based ssvep bci," *Measurement*, vol. 196, p. 111188, 2022.

[30] J. Kooij, D. Bijlenga, L. Salerno, R. Jaeschke, I. Bitter, J. Balázs, J. Thome, G. Dom, S. Kasper, C. N. Filipe, *et al.*, "Updated european consensus statement on diagnosis and treatment of adult adhd," *European psychiatry*, vol. 56, pp. 14–34, 2019.

[31] P. Arpaia, S. Criscuolo, E. De Benedetto, N. Donato, and L. Duraccio, "A wearable ar-based bci for robot control in adhd treatment: Preliminary evaluation of adherence to therapy," in *2021 15th International Conference on Advanced Technologies, Systems and Services in Telecommunications (TELSIKS)*, pp. 321–324, IEEE, 2021.

[32] "*Italian Battery for ADHD* website." https://disturbiapprendimento.myblog.it/media/01/00/1379102928.pdf. [Online; accessed 11-June-2022].