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Robotic Autism Rehabilitation by Wearable Brain-Computer Interface and Augmented Reality

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***Abstract*—An instrument based on the integration of Brain Computer Interface (BCI) and Augmented Reality (AR) is proposed for robotic autism rehabilitation. Flickering stimuli at fixed frequencies appear on the display of Augmented Reality (AR) glasses. When the user focuses on one of the stimuli a Steady State Visual Evoked Potentials (SSVEP) occurs on his occipital region. A single-channel electroencephalographic Brain Computer Interface detects the elicited SSVEP and sends the corresponding commands to a mobile robot. The device's high wearability (single channel and dry electrodes), and the trainingless usability are fundamental for the acceptance by Autism Spectrum Disorder (ASD) children. Effectively controlling the movements of a robot through a new channel enhances rehabilitation engagement and effectiveness. A case study at an accredited rehabilitation center on 10 healthy adult subjects highlighted an average accuracy higher than 83%. Preliminary further tests at the Department of Translational Medical Sciences of University of Naples Federico II on 3 ASD patients between 8 and 10 years old provided positive feedback on device acceptance and attentional performance.**

I. Introduction

Autism Spectrum Disorders (ASDs) are a class of complex neurobehavioral conditions, characterized by an impairment of social interaction, verbal and non-verbal communication, repetitive and stereotypical forms of behavior, and rigidity in the habits [1]. ASD symptoms appear during the first three years of life and may change over time. Lack of social skills and a reduced ability to determine when to use these skills also contribute to the overall disability. Some manifestations of ASD include delays in cognitive development, language, gestures and movements, in the capacity of imagination, in symbolic play and in recognizing emotions; presence of sensory hypersensitivity [1], lack in executive functions [2] and in learning how to conduct crucial activities of daily living.

About 1 in 59 children has been identified with autism spectrum disorder according to estimates from CDC's Autism and Developmental Disabilities Monitoring (ADDM) Network. The gender gap has decreased. While boys were 4 times more likely to be diagnosed than girls (1 in 37 versus 1 in 151) in 2014, the difference was narrower than in 2012, when boys were 4.5 times more frequently diagnosed than girls [3].

Different approaches of therapy for ASD are available; however, a single program or regimen is not effective for all individuals with ASD. This may be due to large variations in skill level, cognitive ability, coping ability, and the type and number of specific challenges manifested in each individual with this spectrum disorder [1], [4]. Over the past several years, computer-assisted and robot-assisted therapies have been infiltrating the social skills teaching environment. Rapid progress in the field of technology, especially in the robotics area, offers important possibilities for innovation and treatment or even education for individuals with ASD. The emergent robotic and technological literature has demonstrated that many individuals with ASD show a preference for robot-like characteristics over non-robotic toys [5] and in some circumstances even respond faster when cued by robotic movement rather than human movement [6]. Researchers investigating robots as ASD therapy tools often report increased engagement, increased levels of attention, and novel social behaviors such as joint attention and spontaneous imitation when robots are part of the interaction [7], [8]. Golan and Baron-Cohen [9] suggested that the use of computerized intervention in ASD individuals enables the development of skills in a highly standardized, predictable, and controlled environment, while simultaneously allowing an individual to work at his own pace and ability level.

Among the behavioral approaches, Brain computer Interface (BCI) has often been proposed as an innovative method for treatment of ASD [10]. The review provided by Friedrich

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et al. [11], grounded on a series of neurofeedback training studies, postulates that quantitative EEG-based neurofeedback training is viable as a personalized therapeutic approach in ASD. Concerning cognitive applications in the field of neuro-rehabilitation the use of combined Virtual Reality (VR) and BCIs has mainly been used with children with attention deficit hyperactivity disorder (which includes the presence of frequent inattentive, impulsive and hyperactive behaviours [1]). For example, Cho et al. [12] tested an attention enhancement system using a head mounted Virtual Reality device and EEG biofeedback to increase the attention span of children who have attention difficulties. A summary of several studies, that have examined the feasibility and effectiveness of VR as a social skill training option for people with ASD, can find in Wainer & Ingersoll, 2011; Wang & Reid, 2011 [13] . The majority of these studies focused on teaching emotion recognition and simple language skills such as learning vocabulary words and receptive language. More recently, Kandalaft and Didehbani [14] tested the efficacy of a Virtual Reality Social Cognition Training tool in children with high functioning autism and measured changes in affect recognition, social attribution, and executive function pre and post training. These studies revealed some promising improvements in social capabilities of ASD subjects, but almost all of them pointed some problems in the translation of these improvements for the individuals' daily living joint attention skills, which represent 'real-world' life demands. A novel virtual-reality P300-based Brain Computer Interface (P300-based BCI paradigm for rehabilitation of joint-attention skills) paradigm, using social cues to direct the focus of attention, was tested in 13 healthy participants, in 3 EEG systems. The more suitable setup was tested online with 4 ASD subjects. Proof of concept tests in ASD participants proved that this setup is feasible for training joint attention skills in ASD [15]. Focusing on the properties of SSVEP signals [16], induced in the primary visual cortex when a user is observing intermittent visual stimuli, and preserving their periodicity, an instrument for remote control of robot by wearable SSVEP-based BCI and AR glasses is proposed for rehabilitating children with ASD and ADHD (Attention Deficit Hyperactivity Disorder) traits is proposed. Section II describes the development of the system, from the basic idea to the hardware chosen. In Section III the experimental results, along with the metrological analysis, are presented. Then, in Section IV, the description of the Case Study is reported. Finally, in Section V the conclusions are drawn.

II. Materials and Methods

In this section, the basic idea and the realization of the system are presented. A SSVEP based single-channel BCI is integrated with a head mounted display AR platform..The application target is a rehabilitation robot providing feedback to the patient remote control, allowing to treat symptoms of inattention, hyperactivity, and impulsiveness. The BCI instrumentation consists of two active dry electrodes and a reference electrode. The difference between the signal in the occipital and the frontal regions is taken into account, as

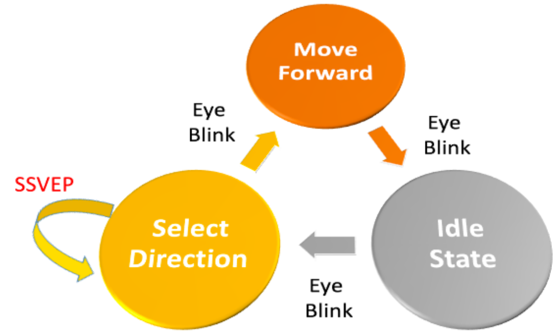

Fig. 1: Instrument Operation.

this configuration allows to successfully remove muscle and eye artifacts [17],[18], and to keep the system wearable. By analyzing user's SSVEP, the BCI instrumentation is able to direct the robot with a fixed, configurable, angle, and to move it forward. The AR platform plays the role of the generator of the flickering stimuli. To this aim, the visual fatigue, the user attention is reduced using only two stimuli. Therefore, the accuracy of the BCI control is increased. The number of available commands is compensated using the eye blink artifacts detection, as explained in Fig.1

A. Hardware

As shown in Fig. 2, the AR *Glasses* render the visual stimuli, eliciting SSVEP responses in the patient. Then, *Acquisition Unit* digitalizes the EEG voltage sensed by the *Electrodes* placed on the scalp. The EEG samples are sent to the *Processing Unit* and, after the processing, the response and the related command are sent to the robot via *TCP/IP* protocol. In addiction to its movements, an acoustic feedback is foreseen by the robot. In particular, the hardware of the system is composed as follows:

- *Acquisition Unit:* EEG Signals were captured using (i) two active electrodes positioned at the Frontal Midline (Fpz) and the Occipital Midline (Oz) positions, according to the international system 10-20 [17], and (ii) a passive electrode (acting as reference), placed on the

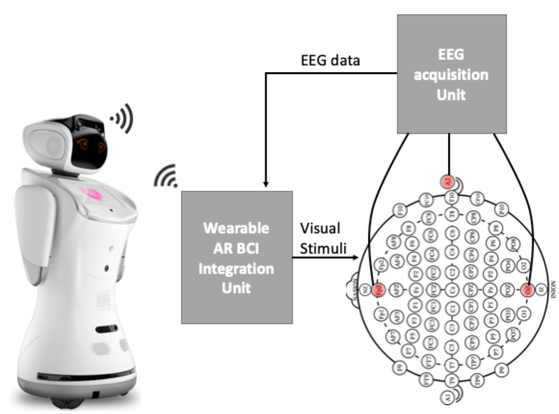

Fig. 2: Instrument architecture.

wrist. Signals were then digitized using the Olimex EEG-SMT, a 10-bit, 256 S/s, differential input Analog-Digital Converter (ADC) (More info available at [19]).

- *Processing Unit:* A single-board computer Raspberry Pi 3 (More info available at [20]) was used as processing unit and server, to provide the information extrapolated from the data received via USB from the Olimex.
- *Glasses:* The stimulation unit was developed using the Moverio BT-200 AR smart glasses (More info available at [21]). The perceived screen size of the glasses is 2 m at 5 m projected distance, and the refresh rate is 60 Hz. Two white flickering arrows, related to the commands "move to the left" and "move to the right", represent the AR interface. Fig.3 show their positions in the screen.
- *Robot:* The target of this application was a SanBot Elf (More info available at [22]), a humanoid robot developed and produced by Qihan Technology Co. The purpose of this application was to direct the robot to the left, to the right, stopping it and making it move forward according to the user wishes. Moreover, a sonorous feedback about its movement is foreseen. The robot was connected trough Wi-Fi to the Raspberry Pi server, retrieving information in a JSON format.

B. Operation

The user wears the AR glasses and launches the Android application for rendering the flickering stimuli to pilot the robot. Then, as visible in Fig. 1, the user is able to set the three states of the robot by means of voluntary eye blinks. When the robot is in the state "Change Direction", the user, keeping a focus around one stimulus out of two, makes the system send the desired command to the robot (as an example, *move to the right*). Then, by an eye blink, the robot moves forward. A further eye blink stops, finally, the robot.

C. Processing

- *SSVEP* Frequency Recognition: a correlation-based algorithm [18] is used to recognize the frequency elicited by the observed stimulus. Given a time window of duration *T*, the related signal fragment is filtered using a passband FIR filter between 5 and 25 Hz. Then, the Pearson correlation coefficients ρ_1 and ρ_2 are assessed between the filtered data D_f and two sine waveforms Υ_1, and Υ_2, at the same frequency of the corresponding flickering stimuli and variable phase ϕ:

$$\rho_1 = \max_{\phi\in[0,2\pi]} \frac{cov(D_f, \Upsilon_1(\phi))}{\sigma_{D_f}\,\sigma_{\Upsilon_1(\phi)}} \tag{1}$$

$$\rho_2 = \max_{\phi\in[0,2\pi]} \frac{cov(D_f, \Upsilon_2(\phi))}{\sigma_{D_f}\,\sigma_{\Upsilon_2(\phi)}} \tag{2}$$

The following features are then extracted

$$\lambda_1 = max(\rho_1, \rho_2) \tag{3}$$

$$\lambda_2 = \frac{max(\rho_1, \rho_2) - min(\rho_1, \rho_2)}{min(\rho_1, \rho_2)} \tag{4}$$

where D_f are the filtered Data, Υ_1 and Υ_2 the two sinewaves, ϕ is the phase, σ_D the standard deviation of the filtered data, and σ_Υ the standard deviation of the sinewaves.

$$\lambda_1 > th_1 \quad \cap \quad \lambda_2 > th_2 \tag{5}$$

Where th_1 and th_2 are two threshold values; th_1 is the maximum value among all the Pearson Correlation Coefficients evaluated, and is an index of how much the EEG signal is correlated with the one of the two stimuli. th_2 represents how much ρ_1 is greater than ρ_2. For example, by setting a threshold value for th_2 equal to 0.50, the condition 5 is satisfied if ρ_1 is greater at least 50% more than ρ_2 If condition (5) is not satisfied, a new fragment of length *T*, overlapping with the previous one by *T/2*, is processed.

- *Eye blink detection:* Voluntary eye blinks are tipically characterized by negative peaks along the EEG track. Such peaks are exploited to distinguish voluntary and involuntary eye blinks when the signal exceeds a fixed threshold in normalized units, as shown in Fig. 4

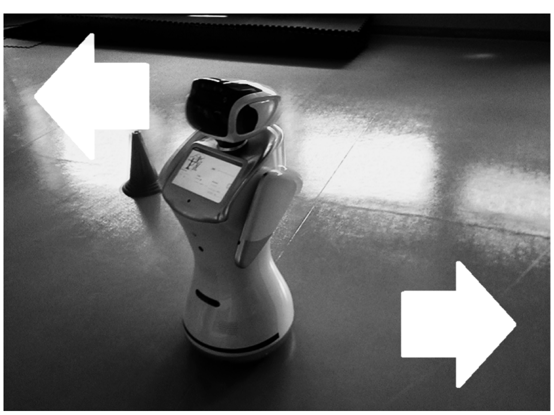

Fig. 3: Capture of users' view

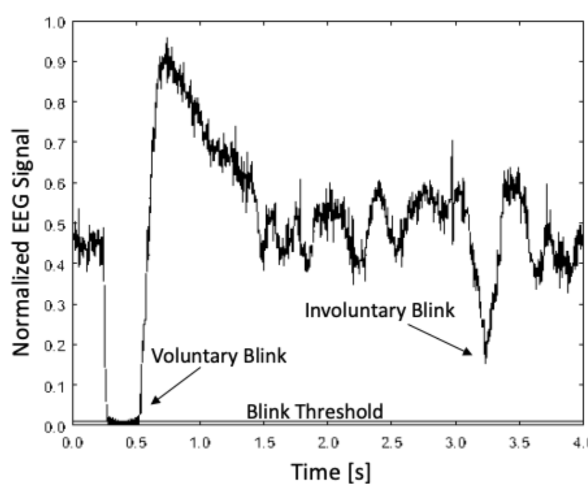

Fig. 4: Eye Blink Detection

III. Experimental Results

- *SSVEP detection*: the characterization of the SSVEP detection algorithm in terms of accuracy and response time was performed, based on a previous experimental campaign carried out in [18], where 24 brain signals were acquired for each of the 20 healthy and untrained volunteers. The flickering frequencies were 10 Hz (on the right side of the screen) and 12 Hz (on the left), based on the studies reported in [23]. Table I shows the performance measured at 2-σ in terms of accuracy, defined as the number of correct decision divided by the number of total decision, and latency, defined as the time required to the algorithm to make a decision. The parameters for SSVEP detection are chosen as follows:
  - T = 0.5 s
  - th_1, th_2 = 0.50
- *Eye Blink detection*: 10 users were left free to blink their eyes without focusing on any of the two stimuli. The threshold value for eye blink detection was set to 0 (normalized unit). The performance at 2-σ in terms of accuracy, defined exactly as done for SSVEP, of the eye blink detection algorithm are shown in Table II. No latency is required for the eye blink recognition.
- *SSVEP-Eye blink integrated algorithm*: furthermore, by means of a Java application, the accuracy of the overall system (AR/BCI/Robot) was performed. Such a software received the commands sent by the Raspberry and simulated exactly the robot behaviour. 10 subjects were asked to make the virtual robot reach a target, moving it inside a maze, as highlighted in Fig. 5. The Accuracy measured at 2-σ was equal to (83.5 $\pm$ 2.9)%, over an average number of 34 $\pm$ 6 commands [18].

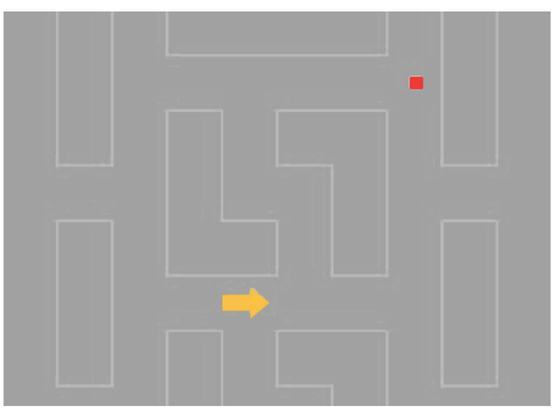

Fig. 5: Java application simulating robot behaviour

IV. Clinical ASD Case Study

The preliminary on-field validation was performed on 3 untrained children, from 8 to 10 years old affected by ASD and ADHD traits, with different functioning. The first one was 9 years and 2 months, with a diagnosis of ASD, 1^{st} *specifier*: without accompanying intellectual impairment; 2^{nd} *specifier*: without accompanying language impairment according to DSM-5 criteria [1]; and with a diagnosis in comorbidity of ADHD, *Combined Type*, according to DSM-5 criteria. The patient is on psychopharmacological treatment with methylphenidate; and he was waiting to start rehabilitation treatment. A psychodiagnostic evaluation, with standardised tests, showed the following results: IQ of 87, compatible with normal cognitive skills, tested with LEITER-R [24]; ADOS 2 Module 3 [25], for the evaluation of communication, social interaction, play, and restricted and repetitive behaviours, showed a comparison score of 6, compatible with a moderate level of symptoms related to ASD; the level of functional impairment assessed by the Clinical Global Impression (CGI) scale [26] showed a score of 3, compatible with a disease severity corresponding to a *Mildly ill*. In conclusion, the patient presented a slight functional impairment both for communicative-relational symptoms and for the symptoms of inattention, hyperactivity and impulsivity. The second child was 8 years and 7 months, with a diagnosis of ASD, 1^{st} *specifier*: with accompanying intellectual impairment; 2^{nd} *specifier*: with accompanying language impairment according to DSM-5 criteria; and with a diagnosis in comorbidity of ADHD, *Combined Type*, according to DSM-5 criteria. The patient was on psychopharmacological treatment with

TABLE I: SSVEP detection algorithm

Volunteer	Accuracy (%)	Latency (s)
#1	70.8	0.96 $\pm$ 0.25
#2	87.5	1.20 $\pm$ 0.40
#3	66.7	1.50 $\pm$ 0.50
#4	100.0	1.02 $\pm$ 0.25
#5	95.8	1.05 $\pm$ 0.19
#6	62.5	1.94 $\pm$ 0.44
#7	91.7	0.68 $\pm$ 0.13
#8	70.8	1.67 $\pm$ 0.48
#9	91.7	0.65 $\pm$ 0.11
#10	83.3	1.13 $\pm$ 0.43
#11	100.0	0.61 $\pm$ 0.08
#12	83.3	0.83 $\pm$ 0.16
#13	66.7	1.78 $\pm$ 0.43
#14	83.3	1.87 $\pm$ 0.77
#15	91.7	0.63 $\pm$ 0.08
#16	75.0	1.35 $\pm$ 0.37
#17	45.8	1.13 $\pm$ 0.25
#18	70.8	1.85 $\pm$ 0.69
#19	70.8	1.22 $\pm$ 0.39
#20	62.5	1.26 $\pm$ 0.26
Results	78.5 $\pm$ 6.5	1.22 $\pm$ 0.42

TABLE II: Eye blink detection algorithm

Volunteer	Voluntary Blinks	Errors	Unvoluntary Blinks	Errors	Accuracy (%)
#1	10	0	10	3	85
#2	10	0	10	1	95
#3	10	0	10	1	95
#4	10	0	10	0	100
#5	10	0	10	2	90
#6	10	0	10	2	90
#7	10	0	10	1	95
#8	10	0	10	0	100
#9	10	0	10	2	90
#10	10	0	10	2	90
Results	100	0	100	14	93 $\pm$ 3

methylphenidate; and he benefited from Cognitive Behavioral Therapy of 14 hours for week. The psychodiagnostic evaluation showed: IQ of 57, compatible with mild cognitive impairment, tested with LEITER-R; ADOS 2 Module 2 showed a result compatible with a symptomatology of ASD but with an assessment affected by reduced attention and hyperactivity; Conners scales- Parents version [27] presented clinically significant results for inattention, hyperactivity, ADHD; the level of functional impairment assessed by the CGI scale showed a score of 4, compatible with a disease severity corresponding to a *Moderately ill*. In conclusion, the patient presented a moderate functional impairment for communicative-relational symptoms and a marked functional impairment for the symptoms of inattention, hyperactivity and impulsivity. The last one was 10 years and 7 months, with a diagnosis of ASD, 1^{st} *specifier*: with accompanying intellectual impairment; 2^{nd} *specifier*: with accompanying language impairment according to DSM-5 criteria; and presence of ADHD traits which however did not meet the diagnostic criteria for comorbid ADHD. The patient was not on psychopharmacological treatment; but he benefited from Cognitive Behavioral Therapy of 15 hours for week. The psychodiagnostic evaluation showed: IQ of 69, compatible with mild cognitive impairment, tested with LEITER-R; ADOS 2 Module 2 showed a comparison score of 6, compatible with a moderate level of symptoms related to ASD; CARS2-ST Scales showed [28] a total score of 39.2, compatible with the presence of severe symptoms of ASD; the level of functional impairment assessed by the CGI scale showed a score of 5, compatible with a disease severity corresponding to a *Markedly ill*. In conclusion, the patient presented a marked functional impairment for communicative-relational symptoms and a slight functional impairment for the symptoms of inattention, hyperactivity and impulsivity.

By means of the SSVEP/eye blink detection it was possible to move the robot as follows:

- *10 Hz:* move to the right (with a rotation angle of $\frac{\pi}{4}$ rad);
- *12 Hz:* move to the left (with a rotation angle of $\frac{\pi}{4}$ rad);
- *Eye blink*: change State (move forward, stop, and change direction).

The parameters chosen for SSVEP/Eye blink detection are the same of Tab. I and II. The luminosity of the environment measured was (151 ± 2) lx. Such a value may afflict the accuracy of the system, as more the environment is bright, less the flickering of the stimuli is visible for the user. Each child had the task of piloting the robot to reach targets each time differently positioned. The trial lasted 10 min for each child. The system was presented to the children making them be confident with both the eye blink and the SSVEP detection.

The aim of the experiment was to verify the wearability and the usability of the device, and to evaluate the performance in terms of attention and engagement.

Children were shown a demonstration of how the system works using an adult volunteer. Then, the first child immediately wanted to wear the smart glasses and electrodes, completing the task. The second child was for a moment frightened, then put on the devices voluntarily. He partially completed the task because of electrodes instability due to rapid and continuous movements (the problem can be addressed with an ergonomic development). The third child was reluctant from the beginning and did not want to try the device. However, he gradually approached the robot and activated a custom interaction via touch screen. According to the therapists gradually familiarizing with the system is important in case of patients with high levels of anxiety. Therapists and parents attended the experiment. A short summary of the experiment results is shown in Tab. III.

TABLE III: Clinical case study: Performance of SSVEP/Eye blink integrated detection algorithm

Subject	CGI Score	Initial reluctance	Task completed
#1	3	no	yes
#2	4	yes	yes, partially
#3	5	yes	no

V. Conclusions

The authors propose a system for application in children ASD rehabilitation, using augmented reality smart glasses with a non-invasive single-channel brain-computer interface based on SSVEP. A Robot used in children rehabilitation is driven by untrained users by focusing flickering stimuli and using eye blinking. After the commands are received, the robot gives acoustic and visual feedback to the user. The system manages to overcome challenges related to acceptability and degree of involvement guaranteed by the proposed therapeutic setups in ASD rehabilitation.

A preliminary clinical case study on 10 healthy adult subjects showed an average accuracy of the SSVEP/Eye blink detection algorithm higher than 83%, with a corresponding time response of about 1.5 s. Positive feedback on the device acceptance and attentional performance were offered after tests on 3 ASD patients (with three different CGI scores) between 8 and 10 years. In future work, the use of the proposed system in diagnostic will be explored.

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