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Abstract— This paper identifies the user's adaptation on brain-controlled systems and the ability to control brain-generated events in a closed neuro-feedback loop. To accomplish that, a working system has been developed based on off-the-shelf components for controlling a robot in both the real and virtual world. Using commercial Brain-Computer Interfaces (BCIs) the overall cost, set up time and complexity can be reduced. The system is divided in two prototypes based on the headset type used. The first prototype is based on the Neurosky headset and it has been tested with 54 participants. The second prototype is based on the Emotiv headset including more sensors and accuracy. Initial evaluation results indicate that robot navigation through commercial BCIs can be effective and natural.

Keywords – brain-computer interfaces, human-robot interaction, serious games, virtual worlds.

I. INTRODUCTION

Brain-computer interfaces (BCIs) are communication devices which enable users to send commands to a computing device using brain activity only [1]. This technology is a rapidly growing field of research and an interdisciplinary endeavor. Research into BCIs involves knowledge of disciplines such as neuroscience, computer science, engineering and clinical rehabilitation. Brain-controlled robots and serious games can be used for a wide range of applications from modern computer games [2], prosthetics and control systems [3] through to medical diagnostics [4]. Although research on the field started during the 1970's only the last few years it became possible to introduce BCIs mostly through commercial headsets for computer games and other simulations.

There are three categories of BCIs: *invasive*, *partially-invasive* and *non-invasive*. With invasive BCIs the signals are recorded from electrodes implanted surgically over the brain cortex, into the grey matter of the brain during neurosurgery. Partially-invasive BCIs are implanted inside the skull but rest outside the brain rather than within the grey matter. Non-invasive BCIs operate by recording the brain activity from the scalp with EEG sensors attached to the head on an electrode cap or headset without being surgically implanted.

Electroencephalography (EEG) is the most studied non-invasive interface, mainly due to its portability, ease of use and low set-up cost [5]. The raw EEG is usually described in terms of frequency ranges: Gamma (γ) greater than 30 Hz, Beta (β) 13-30 Hz, Alpha (α) 8-12 Hz, Theta (θ) 4-8 Hz, and Delta (δ) less than 4 Hz [6]. Delta (δ) waves with the lowest frequencies of all the brainwaves are most apparent in deep sleep states, where conscious brain activity is minimal. Theta (θ) waves appear in a relaxed state and during light sleep and meditation. Alpha (α) waves are typically associated with meditation and relaxation, more so than any other waves. Beta (β) waves are connected to alertness and focus. Gamma (γ) waves can be stimulated by meditating while focusing on a specific object.

Early research on the area began from UCLA in the 1970's introducing the term 'Brain-Computer Interface' [7], [8]. It was mainly focused on neuro-prosthetics which aimed at restoring damaged hearing, sight and movement. Over the past decades, researchers developed systems that carry out movements of robotic arms handled by monkeys getting biofeedback. This allowed to map patterns of the neural activity of the brain and to develop novel algorithms. Around 20 years later, researchers at University of California, Berkeley, decoded neuronal firings to reproduce images seen by cats. They decoded signals from the targeted brain cells of the cats' brain, and reconstructed images of what the cats saw [9].

In the 1980s, researchers at Johns Hopkins University found a mathematical relationship between the electrical responses of single motor-cortex neurons in rhesus macaque monkeys as well as the direction that monkeys moved their arms [10]. Later experiments using rhesus monkeys researchers reproduced reaching and grasping movements in a robotic arm [11]. By mid 90's invasive BCI's have started applied into humans. One example of invasive BCI is the direct brain implant to treat non-congenital blindness. Sixty-eight electrodes were implanted into the patient's visual cortex and succeeded in producing phosphenes, the sensation of seeing light without light actually entering the eye, through cameras that were mounted on glasses to send signals to the implant [12]. In 1998, researchers at Emory University in Atlanta installed a brain implant into a human that produced signals of high enough quality to simulate movement [13]. More recently, researchers succeeded in building a BCI that reproduced owl monkey movements while the monkey operated a

joystick or reached for food [14]. Moreover, in 2004, researchers from Washington University in St Louis enabled a teenage boy to play Space Invaders using his Electrocorticography (ECoG) implant, a partially invasive BCI device [15].

The past few years' various ways in controlling robotic platforms (mainly electrical wheelchairs or robotic arms) for people suffering from a diverse range of impairments were investigated [16], [17]. Patients suffering from 'locked-in syndrome', spinal cord injury or damaged regions of the brain responsible for the body movement have used BCIs focusing on motor neuroprosthetics in order to rehabilitate or assist their interaction with the outside world [18]. With the launch of commercial headsets, as an alternative gaming controller, BCIs appeared in the computer gaming domain. This allowed researchers to start developing various novel applications with relatively low cost non-invasive EEG equipment and software development kits (SDKs). This technology boosted the BCI's in games oriented research with main target medical applications and brain rehabilitation through the use of serious games and virtual worlds. Furthermore, gaming technology has been assisted by virtual and augmented reality systems, making hybrid BCI systems for enhancing the user experience, study and improvement of brain-computer interaction [2].

This research focuses on how a robot operated through brainwaves can overcome the kinetic constraints of the user. It investigates ways in extracting valuable information from user's brain activity by interacting with both real world objects and virtual world environments. The experimental prototype uses the basic movement operations of a Lego Mindstroms NXT Robot. There are two versions of this prototype, taking readings from the users' brain electrical activity in real-time performance. The first version is made by using a single dry sensor headset from Neurosky using the attention levels of the user. The second version is using a 14 wet sensor headset from Emotiv taking readings not only from EEG signals but also from facial expressions, eye movement and head tilt enabling the user to fully control the robot with the required user training. Initial evaluation results indicate that robot navigation through commercial BCIs can be effective and natural.

The rest of the paper is structured as follows. Section II provides a brief overview of similar systems and section III presents an overview of our system. Sections IV and V present the two experimental prototypes that were implemented. Finally, section VI illustrates initial evaluation results and section VII presents conclusions and future work.

II. BACKGROUND

Non-invasive BCI research methods in serious games development are usually oriented in the medical domain rather than entertainment. An early study developed an internet game linked to a BCI. The system translated real-time brain activities from prefrontal cortex (PFC) or hippocampaus (CA1) of a rat into external device control commands and used them to drive an internet game called RaviDuel [19]. Another BCI based 3D game measured user's attention level to control a virtual hand's movement, making use of 3D animation techniques. This system has been developed for training those who suffering from Attention Deficit Hyperactivity Disorder (ADHD) [20]. In another study, researchers focused on the design and implementation of a game capable of moving an avatar from a tennis game using only brain activity [21]. This can assist people with diseases involving movement difficulties for controlling keyboard and mouse of a computer. To achieve this, the mu (μ) rhythm of brain activity has been used [22].

An EEG pattern recognition system has been designed to adapt a serious game by comparing recognition rates for experimental purposes without any traditional controllers. Their proposed Support Vector Machine (SVM) algorithm for classification is compared with other algorithms, improving the recognition rate [23]. A Quantitative and Qualitative Study in Self-Paced Brain-Computer Interaction with Virtual Worlds showed that, without training, roughly half of the subjects were able to control the application by using real foot movements and a quarter were able to control it by using imagined foot movements. The application consisted of an interaction with a virtual world inspired by the "Star Wars" movie. Participants were asked to control the take-off and height of a virtual spaceship using their motor-related brain activity [24].

III. SYSTEM OVERVIEW

The basic hardware components of the project include two EEG headsets: the Neurosky (Mindset and Mindwave), and the Emotiv Epoc EEG headset. Additionally, a LEGO Mindstorms NXT robot, a desktop computer, an Ultra-Mobile PC (UMPC) and a Netbook PC were used. The software components include a computer simulation with a 3D reconstruction of the NXT robot, a JAVA application for the physical robot and a client/server program that establishes connection with both the physical robot and the simulation.

The Neurosky headsets have been used to extract the Attention and Meditation levels of the user. The headset is calculating the Raw EEG signals to produce the "eSense Meters" [25] based on an algorithm patented from Neurosky. The patterns of the electrical activity are analyzed with the help of specialized algorithms (feature extraction and classification) by converting the EEG signals into control commands.

The Neurosky headset is using a single dry sensor attached to the forehead outside the cerebral cortex in the frontal lobe of the brain being responsible for the attention level and short-term memory tasks. The Emotiv EPOC Headset is using 14 saline sensors being able not only to detect brain signals but also user's facial expressions, eye movement and head position through a 2 axis gyroscope. The various facial expressions referred to as "Expressiv" by Emotiv, levels of engagement,

frustration, meditation, and excitement as "Affectiv"; and training and detection of certain cognitive neuro-activities such as "push", "pull", "rotate", and "lift" as "Cognitiv" [26].

By measuring these brainwaves, these headsets can infer which mental state the user is. Providing all the brain activity details on a computer, the user is able to receive a closed neuro-feedback loop. This is a type of biofeedback that can be useful for the analysis and development of tools that can help people with severe brain damage, for brain rehabilitation or enable them to control a computer program or robotic device.

For the robot, the Lego Mindstorms NXT kit was used with a Java Virtual Machine (JVM) installed. This tiny JVM for ARM processors (called LeJOS) was ported to the NXT robot in 2006. The main advantage of LeJOS NXJ is that it provides the extensibility and adaptability of the JAVA language [27]. The robot version that was used includes a 32-bit AT91SAM7S256 (ARM7TDMI) main microprocessor at 48 MHz (256 KB flash memory, 64 KB RAM). It includes five different types of sensors such as: *servo motors*, *touch*, *light*, *sound* and *ultrasonic*.
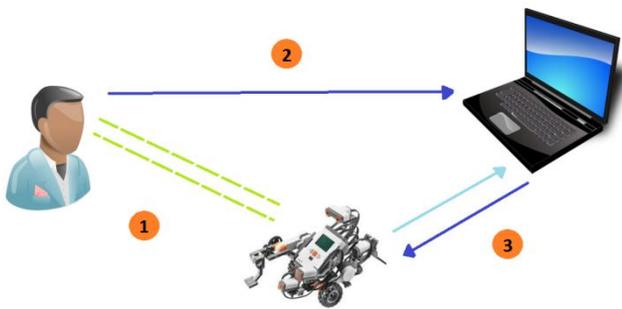

Figure 1 Overview of the system

The touch sensor has been implemented in the prototype to allow collision detection with the real environment. The light sensor is also used as a height detector on this model [28]. An abstract way that this prototype works with the headsets is illustrated on Figure 1, were the user is visually stimulated; the raw data is calculated on the headsets chip and then sent to the dedicated computer. Afterwards, a client/server program instructs the robot to move based on the user brain-activity (or muscular movement) both on real and virtual world. The robot terminates the connection when it hits an obstacle or is stopped by the user.

IV.   FIRST PROTOTYPE (NEUROSKY)

Two types of Neurosky headsets were used for this research (see Figure 2). The main difference between them is that the "Mindset" (left) is a complete headset with speakers and microphone transmitting data on bluetooth while the "Mindwave" (right) comes without a headset and transmits data using radio frequency.

Figure 2 Neurosky Mindset (left), Mindwave (right)

Both headsets use the same ThinkGear Communications Driver (TGCD) library from Neurosky's Development Tools. After establishing connection with the headset, both the physical and virtual robot connects on the client/server application to send instructions through sockets. The first step in communicating is to establish a connection (which has an initiator and a receiver). The receiver waits for a connection from the initiator.

The initiator is the dedicated PC running the client/server program and the receiver is the NXT Robot including both the physical and the computer simulation. The application running in the robot waits for Bluetooth connection; when the PC program establishes connection with the headset, it initiates a connection with the robot and the simulation to send instructions in the client/server architecture. When the connection has been established, both ends of the connection can 'open' input and output streams and read/write data. The computer sends integers (in the range 0 to 100) to the robot depending on the attention levels of the user. Based on those inputs the robot performs actions by sending feedback back to the computer. In this case, if the bumper sensor has been pressed the session is terminated in both ends.

V.   SECOND PROTOTYPE (EMOTIV)

Based on the first prototype, a more advanced version has been created, with the robot performing basic maneuvering (moving forwards, backwards, turn left and turn right) using the Emotiv Epoc headset. The basic idea is to use the Cognitive functions (brainwaves) to move the robot forwards/backwards, and the Expressive functions to steer the robot left/right when the user blinks accordingly. The Emotiv Epoc Headset is a neuro-signal acquisition and processing wireless neuro-headset with 14 wet sensors (and 2 reference sensors) being able to detect brain signals and user's facial expressions, offering optimal positioning for accurate spatial resolution [4]. An integrated gyroscope generates positional information for cursor and camera controls, connected wirelessly through a USB dongle and comes with a lithium battery providing 12 hours of continuous use. The sixteen (14 plus 2 reference) sensors are placed on the international 10-20 system [11], an internationally recognized method which describes the electrode

placement on the scalp for EEG tests or experiments as illustrated in Figure 3.
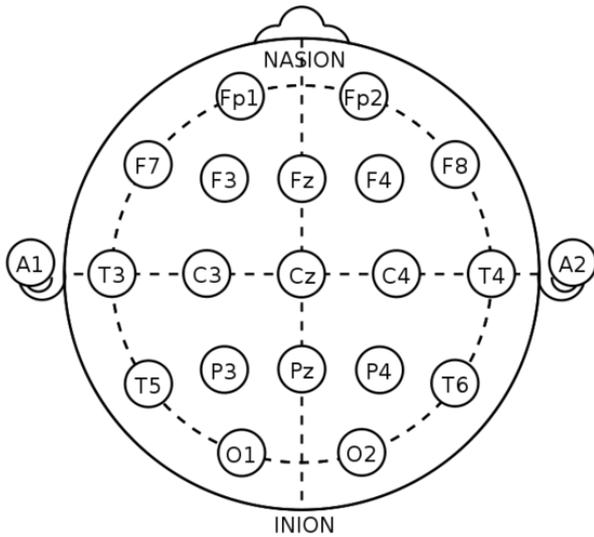

Figure 3 International 10-20 system placement and number designation

The system is fully operational and it relies on a combination of Cognitive and Facial/Muscular functions [29]. In terms of the implementation, the Emotiv Development Kit was used connecting the Emotiv Epoc headset to the Emotiv control panel to create and train a new user profile. The Cognitive functions (brainwaves) are used to move the robot forwards/backwards, and the Expressive functions to steer the robot left/right when the user blinks accordingly. Unlike the Neurosky Mindset (which uses only one dry sensor and does not require user training), Emotiv needs a unique user profile to be trained to map users' brain-patters. In a training session no more than 1 hour, user's skills increased approximately up to 45% for the forward & backward moves and around 10% for left & right.

Training the profile requires practice and familiarization, especially when the user needs to train more than two actions as it is easy to get distracted from outside stimuli and 'confuse' the training process of the users real 'intentions'. To take control of the events the EmoKey application was used connected with Emotiv Control Panel to generate keyboard events for each identified and trained thought. After that the EmoKey application transferrs these events to a key-reading client/server application with each event being treated as 'thought', passing it through a socket connection to the physical robot and the computer simulation.

Moreover, the 3D environment has been designed using the 'Unity 3D' game engine with a 3D reconstruction of the robot, navigating through a simple maze. Unity 3D is an integrated development environment for computer game design and runs on Microsoft Windows and Mac OS X [30]. For this simulation both C# and Javascript programming languages were used. On the computer simulation, the user navigates the robot through the maze and reaches

the end using the Emotiv headset. An example screenshot of the game is illustrated in Figure 4.

Figure 4 The robot navigating through the maze

It is worth-mentioning, that for this prototype an Ultra Mobile PC (UMPC) was used attached to the robot for movement independency as shown on Figure 12. This UMPC carries an Intel Core Solo U1500 processor at 1.33 GHz, 1GB DDR2 RAM, 32GB Solid state drive, running Windows.

Figure 5 NXT robot with UMPC attached

The Emotiv version seems to have the appropriate attributes needed for a robust multimodal BCI-Robot system by making use of all the available user inputs.

VI.   INITIAL EVALUATION

To identify how fast the users adapt on brain-generated events, an initial evaluation has been conducted for three days in a national technology exhibition centre. Neurosky headset was used for this evaluation, as it is easier to set-up and does not require any user training. The testing was hosted at "The Gadget Show Live 2011" at the NEC, Birmingham and 54 participants tested the prototype. The Gadget Show Live is UK's ultimate consumer electronics and gadgets event with hundreds of exhibitors from all over the world and thousands of visitors from all over the UK. This was a

unique opportunity to gather data and feedback for further analysis and improvements of the application. After each testing session, users completed a questionnaire, collecting initial feedback regarding the overall navigation experience with the Neurosky "Mindset" and the robot.

A. Qualitative Evaluation

For this part, participants had to complete a quick and easy task. That was to move the robot forwards, accelerate up to a point and finally try to decelerate and stop it before the end of a small track. All participants used for the first time their brainwaves to interact with the robot. However, even if the Neurosky headset does not require any training, for some users it was quite a unique experience and hard to adapt in taking control straight away. Some of themfound it a strange experience to concentrate and tele-operate a robot with only their brain power. Allowing them a few minutes to familiarise participants started to get control and adapt to the prototype system. The majority of them reported that they have been amazed from the fast response (latency around 1 sec) of the robot as they tried to move it forwards and then stop it.

A common problem that was reported was external distractions which produced unwanted results from the lack of concentration. Some participants found it difficult to stay focused to their task with the external stimuli generated from the people standing around. Another issue that was recorded was the initial excitement of the participants when they saw the robot moving, boosting their attention level as a result to make the robot movement unstable and not being able to stop it. A few participants reported that it was easy to navigate at first, but as soon as you 'feel success and thinking about it, the robot starts to move again'. That made it difficult for some to stay focused and relax in order to stop the robot and complete the task. The task showed that through the continuing neuro-feedback from the system, participants started to adapt and increase their control levels relatively fast (within 5 minutes).

⬆	⬇
• Interesting concept • Could be very useful • Lots of potential • Can increase people's concentration level • Can help improve disabled people's lives • Can help for brain rehabilitation by triggering the motor cortex of the brain • The feel of controlling it with my mind was awesome	• Being able to move left/right • Need some indication on the PC as to the level of thought • Needed less distractions • Difficult to keep the robot stationary • Too many outside stimuli • Hard to remain calm

Table 1   Positive and negative comments that have been reported from the users

Figure 6 demonstrates that the participant ages where almost equally distributed for each age group and as a result the results are more representative.
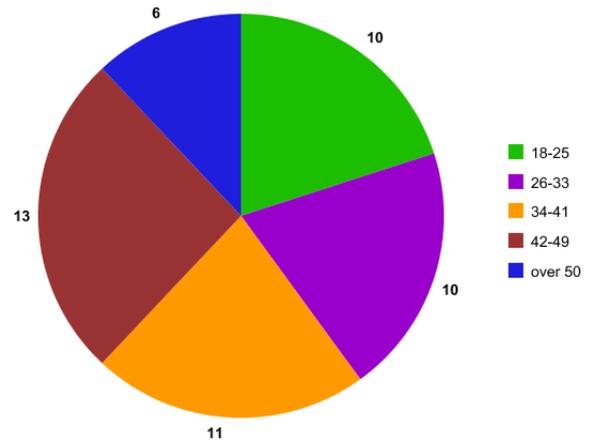

Figure 6 Age group

Since the demonstration took part in the Future Tech Zone of the expedition, men and young children was the vast majority of the participants. As a result the feedback gathered was mainly from males (see Figure 7).
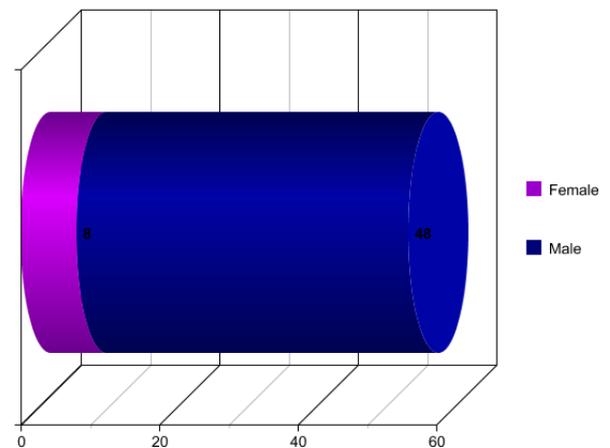

Figure 7 Gender differences

B. Quantitative Evaluation

This section presents the distribution of the participant responses based on their experience with the robot. Each chart has a descriptive label and the answers are based on a 7-point scale. Standard deviation (σ sigma) was used to measure the variation from the average user responses:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

eq. 1

From the square root of the Variance:

$$\mathrm{Var}(X) = \mathrm{E}\left[(X - \mu)^2\right].$$

eq. 2

Averaging the squared differences from the Mean:

$$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$$ eq. 3

	Chart 3 N=54	Chart 4 N=54	Chart 5 N=54	Chart 6 N=52	Chart 7 N=53
Mean (average)	4.2	4.1	4.1	4.2	4.5
Variance	1.4	1.6	1.5	1.6	3.1
Standard Deviation	*1.2*	*1.2*	*1.2*	*1.2*	*1.7*

Table 2   Average and standard deviations

A plot of a normal distribution (or bell curve) has a width of 1 standard deviation. Analyzing the statistical charts below, it is possible to identify a normal distribution on the users' choices with standard deviation of 1.2 as shown on Table 2.
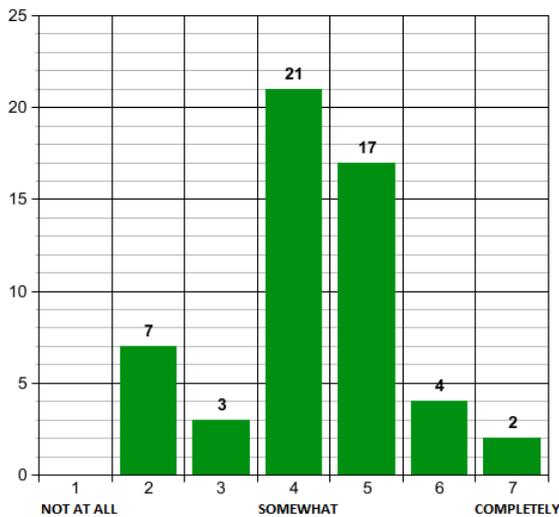

Figure 8 Ability to control events

Figure 8 illustrates the number of participants that were almost (but not completely) able to control the events that have been generated from their brainwaves (to the robot) with an average of 4.2 and standard deviation 1.2 (see Table 2).
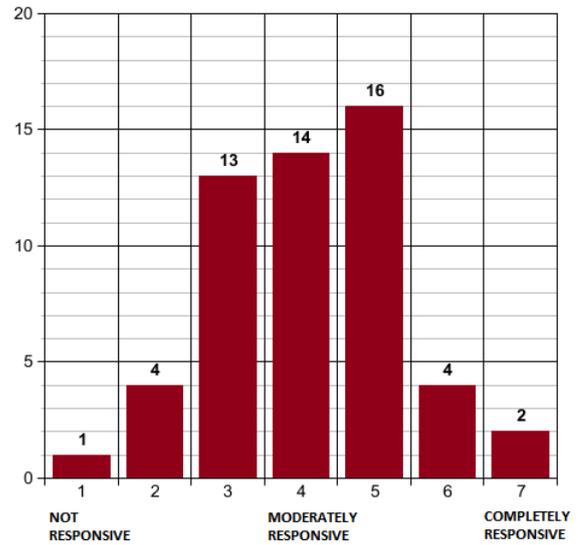

Figure 9 Application responsiveness to actions that have been initiated

Figure 9 illustrates the responsiveness of the robot in relation to the actions that the participants wanted to perform. The majority of them answered between 3 and 5, an average of 4.2 and again a standard deviation of 1.2 (see Table 2).
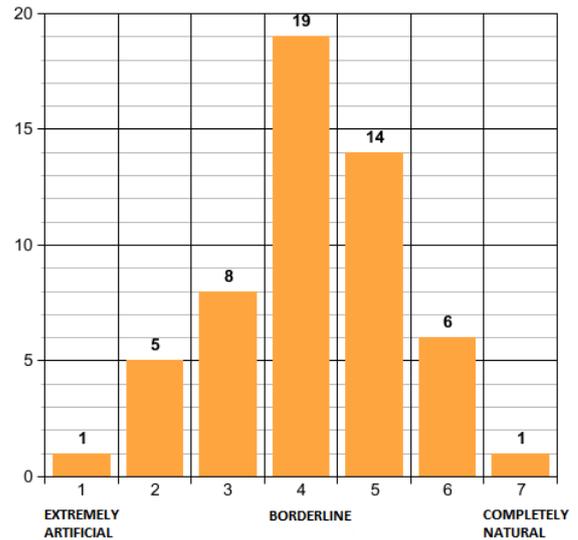

Figure 10 User interactions with the robot

Figure 10 illustrates the effectiveness of the human-robot interaction. It demonstrates how the participants felt when interacting with the robot to perform certain tasks (i.e. move forward and finish the track). The deviation of this chart is the same with Figure 8 and Figure 9 at 1.2 with almost the same average of 4.1 (see Table 2).
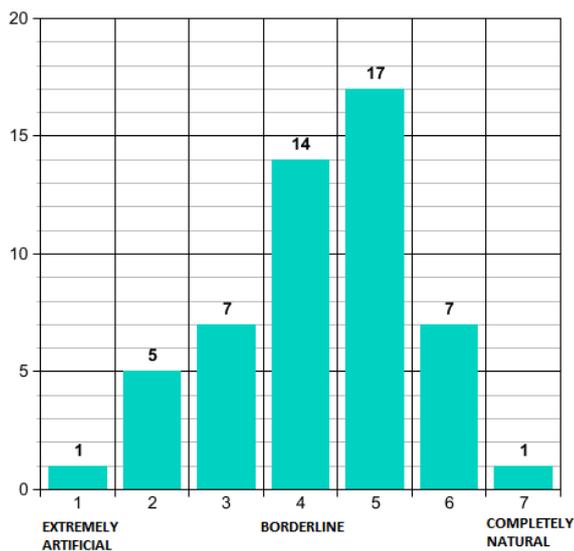
Figure 11 How natural was the mechanism which controlled the robot

Figure 11 illustrates how natural was the mechanism which controlled the robot. Results showed almost identical distribution with the previous Figures and a deviation of 1.2 (see Table 2).
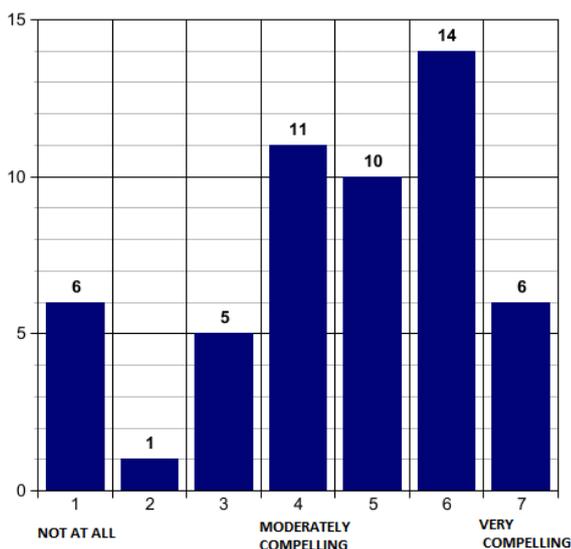

Figure 12 How compelling was the sense of moving the robot

Finally, Figure 12 illustrates how compelling was the participants sense of moving the robot through space. The deviation increased to 1.7 with an average of 4.5 (see Table 2).

VII.   CONCLUSIONS AND FUTURE WORK

This paper presented an affordable human-robot interaction system with commercial and non-invasive BCI headsets using off-the-shelf components for robotic tele-operation. Two prototypes have been experimental tested to discover how easy it is to control brain-generated events in a closed neuro-feedback loop. Initial evaluation results indicate that participants successfully managed to interact with the system on a basic level despite the difficulties of the outside stimuli and the short period of time they had for familiarisation of the BCI technology. Participants managed to adapt in a limited amount of time (a few minutes) in a closed loop interaction with the robot without any previous experience of a similar device and BCI equipment making this research one the few if not the only one that tested a commercial BCI headset in a wide and diverse user group. This may have a profound effect on future user interaction with machines.

Moreover, this research initiates a new generation of serious non-clinical applications for brain rehabilitation with the help of robotic systems or through virtual worlds and serious games. Initial results confirm that an extended user testing is necessary (from different user groups) operating a more robust system and a more detailed comparison of the existing commercial BCI headsets. Our target is to develop a more user-friendly BCI system requiring minimal training and mental load with fewer distractions and outside stimuli, helping the users to efficiently control the system. This kind of research can transform the way we live enhancing human potential through modern technology.

Future work will include the combination of different readings with the use of more sophisticated non-invasive BCI devices equipped with more electrodes and sensors. The development of a virtual environment for brain-user interaction will allow for extensive monitoring and better testing. Furthermore, a large sample of users will be tested to qualitatively measure the effectiveness of the system. Finally, finding ways for additional physiological data extraction, including body posture and facial expression, determine that way user's intentions. This opens up new opportunities and challenges in brain-computer interaction and pervasive computing. Identifying and extracting features from brainwaves (EEG signals) and multimodal systems in a closed feedback loop through serious games.

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