Human-Robotics Interface for the Interaction with Cognitive and Emotional Human Domains

G.L. Mariottini, D. Prattichizzo, M. De Biasi, C. Snickars
Dipartimento di Ingegneria dell'Informazione
Università di Siena
Via Roma 56, 53100 Siena, Italy
Email: {gmariottini,prattichizzo}@dii.unisi.it

A. Rufa†, A. De Capua‡, S. Rossi†
Dep. of Neuroscience, †Sects. Neurology, ‡Psichiatry
Policlinico "Le Scotte", Università di Siena
Siena, Italy
Email: {rufa,decapua,rossisimo}@unisi.it

***Abstract*— For a human-robot interface it is important to have a good model of how the human subject operates. However, since such a model is difficult to obtain, then the robotics interface must observe accurately the subject's behaviour when interacting with him. We present here a new human-robot interface for active interaction with the *cognitive* and *emotional* human domains. Since eye movements convey a lot of information about one subject's cognitive and emotive status, we have designed a new human-robot interface which uses a video-based Eye-Tracker (ET) to observe the subject's line of gaze. Since we are also interested in using our interface for studying and treating depression, our interface can send stimulating inputs to the subject using both a Transcranial Magnetic Stimulator (TMS) and a visual stimulus. The latter elicits the subject's emotions and consists of a set of pictures of facial expressions, which have been shown according to a novel visualization protocol, called Memory-Guided Filtering (MGF). Its effectiveness has been verified by means of many experimental results. We also present the application of our human-robot interface for preliminary studies concerning new cognitive rehabilitation strategies in depression.**

I. INTRODUCTION

The increasing interest toward research in Human-Robot Interaction (HRI), led to the development of a great number of robots of different types (humanoid robots [1], pets [3], medical tools, etc.) in many application areas (entertainment [2], elderly assistance and health care [21], rescue robotics [15], etc.). In the last few years, we have also witnessed a growing interest towards robots that could interact more and more with humans, e.g., for the rehabilitation of *sensorimotor functions*. In order to pursue this goal, the robot must be designed to have some degrees of autonomy to monitor the human and to plan rehabilitation actions to correct the dysfunctional human behaviour [12].

Beyond sensorimotor system, the research on human-robotics interaction interfaces is extending to other fundamental aspects of the human being: the *cognitive* and the *emotion* systems. These two systems are deeply intertwined and they have been recently studied for the design of autonomous robots that must operate in conjunction with people [3]. In order to interact with humans the robot device must have a good model for how the other operates. However, a conceptual model could not be the most appropriate solution when dealing with the emotion system, which is responsible for evaluating and judging events (e.g., good or bad, desirable or undesirable, happiness or sadness, etc.). Then, the robotic device must *observe* accurately the human behaviour and then decide its actions.

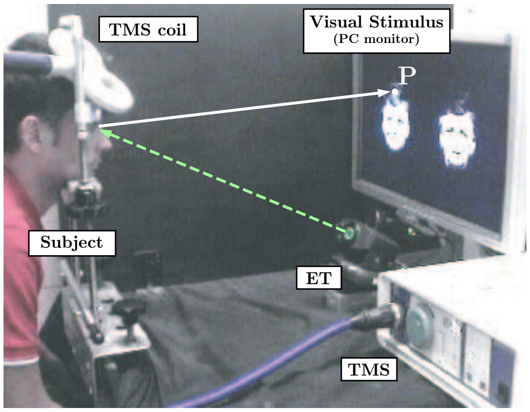


Fig. 1. Human-Robotics Interaction for cognitive and emotional study: software and hardware architecture.

We present here a new human-robotics interface for active interaction with the cognitive and emotional human domains, through a *measurement* system and a *stimulating input* system.

The measurement of the subject's behaviour is provided by a video-based Eye-Tracker (**ET**) (see Fig. 1) that can track the pupil and compute the subject's line of gaze: the eye movements convey a lot of information about one subject's cognitive and emotive status.

Stimulating inputs are given by both a Visual Stimulus and a magnetic stimulus, generated by the Transcranial Magnetic Stimulator (**TMS**) toward some subject's brain areas, through the TMS coil. We use TMS since we are here particularly interested in the applicability of our interface in the study and treatment of depression. In fact, it has been shown that the magnetic field pulses generated by the TMS coil can painlessly and transiently change the mood of depressed patients [17] and change the subjective rate of happiness or sadness [16]. Moreover, the coil position could be efficiently controlled towards specific brain areas by a robotic manipulator to which the TMS coil is fixed. In this way, the HRI will be completely automatized.

The visual stimulus, which appears on a PC monitor, has been designed to stimulate the subject's emotions: we indeed used a set of pictures representing human facial expressions (neutral, sad and happy), which are known to elicit distinct brain activations according to neuroimaging studies [10]. The facial expressions are shown according to a novel visual stimulation protocol, called *Memory Guided Filtering* (MGF), whose robustness in guiding the subject's attention only toward the most important facial expressive features (lips and eyes) has been also experimentally validated. The HRI synchronization between ET and TMS is managed in real-time by the software *ASTIDET* which can also activate the TMS via control signals depending on subject's eye fixation regions.

The original contributions of our work are the following:

- we present the design and implementation of a new human-robotic interface in which ET, TMS and robotic manipulator have been used to allow the interaction with the cognitive and emotional human system (for possible rehabilitation purposes in the treatment of depression);
- ASTIDET software manages the integration and the exact synchronization between ET and TMS;
- subject's emotions are elicited by means of a visual stimulation strategy using a set of pictures representing human facial expressions (neutral, sad and happy), which are presented according to a novel protocol (MGF) whose effectiveness has been observed via many experiments;
- preliminary results on normal subjects and a depressed patient are presented, showing interesting and promising results.

The paper is structured as follows: in Sect.II we present the hardware and software structure of our human-robotics interface. Sect.III describes the visual stimulation protocol MGF and its experimental validation. Finally, in Sect.IV we present preliminary experimental results on normal subjects and depressed patients. In Section.V, we provide some concluding remarks highlighting the main contributions of the paper.

II. THE HUMAN-ROBOT INTERFACE: HARDWARE AND SOFTWARE ARCHITECTURE

A. The eye-tracker device (ET)

The study of ocular movements using non invasive vision based eye-tracker is quite recent and represents an exciting challenge in both engineering and medicine research fields. Video-based ET allows to compute in real-time, using modern computer vision techniques, the subject's *line of gaze* and some other important parameters, such as the pupil diameter [5], [6], [13], [25]. From a medical point of view, the recording of eye movements is an objective evidence to both clinicians and scientists, and is becoming a standard part of psychophysical experimentation [7]. It permits, e.g., to infer and partly understand visual and cognitive behaviours [8].

Refer to Fig. 1: a subject is placed in front of a PC monitor and is asked to look at a visual stimulus (whose characteristics will be described in Sect. III). The eye-tracker (ET) detects in real-time the line of gaze, i.e., the pixel coordinates of the point $P = (x\,,\,y)^T$ where the subject is looking at. We used a robotized pan-tilt ASL Model 504 [13] eye tracker, that can keep the eye in its camera's field of view.

B. The transcranial magnetic stimulator (TMS)

Transcranial magnetic stimulation is a neuromodulatory technique recently employed for cognitive rehabilitation [20]. TMS allows the non invasive and painlessly stimulation of the cerebral cortex of the subject via magnetic field pulses [23] exploiting the principle of magnetic induction. In fact, a rapidly changing current (activated from an external trigger signal) flows from the large capacitor of the TMS (principal unit) to the TMS coils (see Fig. 1), thus producing a magnetic field oriented orthogonally to the plane of the coil, that passes unimpeded through the skin and bones of the subject's head, inducing an oppositely directed current into the brain.

In our experiments we used a Magstim Super Rapid stimulator [14] and an eight-shaped coil (maximum output 2.2 Tesla) that permits to precisely direct the magnetic field to the brain regions of interest. The automatic positioning of the TMS coil to the head is accomplished by the robotic manipulator (to which the coil is fixed), also according to behavioral and clinical information and requirements.

We have chosen to use TMS in our human-robot interface for two reasons: *i)* repetitive TMS (rTMS) delivered on the dorsolateral prefrontal cortex (DLPFC) in depressed patients improves their mood (see [17]); *ii)* rTMS on the left or right DLPFC can change the subjective rate of happiness or sadness [16] in normal subjects. On these basis, we assume that the permanence of the subjects' gaze over happy or sad faces could reflect their empathy towards happiness or sadness feelings. We further predict that eventual rTMS-induced gaze changes could be independent by a direct interference of rTMS on voluntary control of eye movements.

Finally, the technique is safe, provided that ad hoc guidelines are adhered to [24]. Since a more extensive interdisciplinary interaction and analysis is needed when dealing with these advanced topics, this work has been realized in collaboration with neuroscientists. All the subjects were fully informed about the aims of the study.

C. ASTIDET: software for Advanced STImuli Design in Eye-Tracking

ASTIDET v.2.0 is a software package we developed to synchronize the generation of control inputs to the TMS and the acquisition of data from the ET. Integration and exact synchronization of ET and TMS is paramount for our human-robot interface.

The visual stimulus is also generated using ASTIDET which allows to load a set of pictures (Fig. 2-(A)) and define the time instants for picture presentations (Fig. 2-(B)). ASTIDET allows to manage also the control signal properties to the TMS, such as frequency, number of magnetic pulses and starting delay (Fig. 2-(C,D)).

Much effort has been devoted to improve the usability of ASTIDET by means of its Graphical User's Interface (GUI). In fact, due to the interdisciplinarity of our work, we needed to design a software that could be used also by domain experts (physicians, neuroscientists, etc.) more than robotics experts.

We list here the main functionalities of ASTIDET:

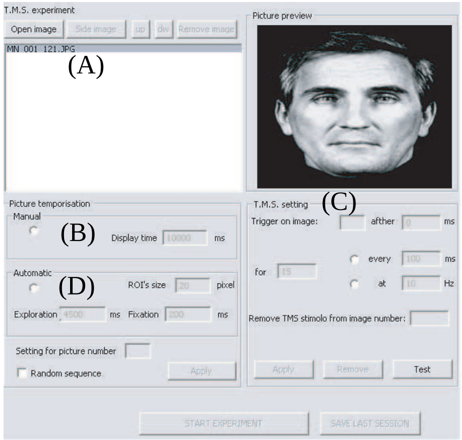
- accurate synchronization between the ET data acquisition and the TMS trigger input generation (with separate threads by MSDN multimedia timers);
- generation of the visual stimuli on the PC monitor (neutral, sad and happy faces);
- storage of the $P = (x, y)$ subject's line of gaze coordinates (in the PC monitor);
- computation of the gaze fixations.

III. VISUAL STIMULATION: THE MGF PROTOCOL

Some recent studies have shown that in patients affected by psychiatric disorders (such as schizophrenia, depression and neurological disorders [10]), there is an impairment in emotional processing, specifically emotion recognition in facial expressions. It is well known that facial expressions convey a wealth of social signals [4]. It has also been shown that the processing of facial expressions can be impaired by means of TMS [9].

Based on the above facts, as introduced in Sect. I, we want to stimulate the subject's emotions by means of the visualization of human facial expressions (neutral, happy and sad) [18].

One of the innovative contributions of this work consists in the design of a novel visual stimulation protocol, according to which the facial expressions are shown: the **MGF** (Memory-Guided Filtering). The peculiarity of MGF is that it does not require any teaching phase of the subject since it has been designed to naturally guide his gaze towards those facial features (lips, mouth and eyes) that are known to convey the expression [11]. The MGF protocol first shows a neutral facial expression (N) for a given time length T_1 (Fig. 3), so that the subject can naturally memorize all the characteristics of the viewed face (hairs, mouth, eyes, nose, etc.). Then, for $t > T_1$, MGF shows at the same time instant a pair of happy (H) and sad (S) facial expressions (Fig. 3), on the left and right side of the screen, respectively. Note that we randomly changed the faces and also their position from an experiment to another (in order to eliminate any kind of bias in the gaze movement).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Exploration 4500 ms Fixation 200 ms
Trigger on image: after 0 ms
for 15
every 100 ms
at 10 Hz

Fig. 2. ASTIDET Graphical User's Interface (GUI) and main functionalities. (A) Load a set of pictures; (B) Define the time lags for which the pictures will appear on the PC monitor; (C) Set the TMS trigger signal properties (frequency and number of pulses); (D) Gaze-contingent properties.

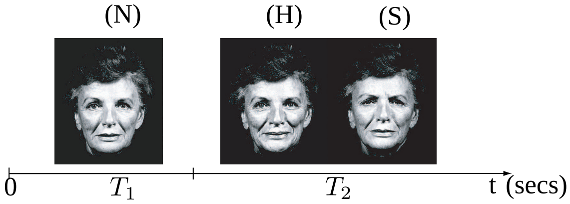


Fig. 3. The Memory Guided Filtering (MGF) protocol.

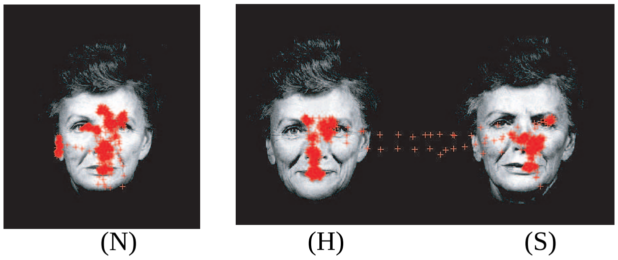


Fig. 4. MGF protocol. (N): during the neutral expression the subject memorizes many features of the face; (H)-(S): the subject's gaze moves from from (H) to (S) images many times in order to memorize the expressions.

MGF has a natural explanation: since the only changes between (N) and the pair (H)-(S), occur in the facial expression features (eyes, lips and mouth) after T_1 then, the subject will only focus his attention to these features after the previous exploration of (N). Fig. 4 shows the effectiveness of the MGF protocol in a real experiment. We have shown here the gaze of a subject exploring the picture during the MGF protocol. For $t < T_1$ the face (N) is presented) and the subject's gaze explores the face focusing on many facial features (eyes, nose and ears) and not only on those conveying the facial expression (see Fig. 4(N). When the happy (H) and sad (S) faces are presented (Fig. 4(H)(S)), the subject spontaneously looks only at those facial features encoding the expression. This behaviour has been observed in all the experiments performed on many subjects and reveals the effectiveness of MGF protocol.

As shown in Fig. 4, when the happy (H) and sad (S) faces are presented, then the subject does not observe exclusively the (H) or (S), but alternatively looks at the two pictures for an exploration phase whose duration is T_e. After T_e, as previously described, we argue that the permanence on a given face may represent a reflection of the subject's empathy toward that face and then, accordingly to the setup in Fig. 1, a trigger signal will be send to the TMS which

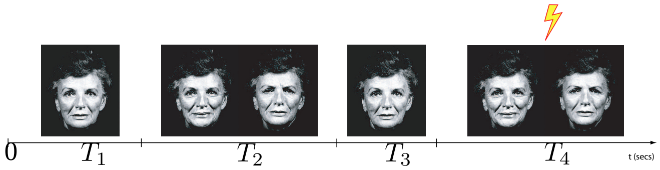


Fig. 5. The Memory Guided Filtering 2 (MGF2) protocol.

will magnetically stimulate the subject's brain.

However, we observed via 150 experiments on 30 subjects, that the duration T_e strongly depends on the subject. This also reflects in an unpredictable (i.e., with high-variability) number n of transitions between the two images.

A. *MGF2*

In order to reduce the variability of the number of transitions n, we have designed the MGF2 protocol. It consists in showing the MGF protocol two times consecutively, as shown in Fig. 5, and in stimulating via TMS only when the pair of happy and sad images is presented for the second time, i.e., during the last period T_4.

In this way, during T_2, the subject can freely explore (H)-(S) thus memorizing the viewed expressions. The first neutral expression (N) is then shown for a short period T_3 (during which the subjects will unconsciously elaborate previously gathered visual information), finally followed by the (H)-(S) stimulus (for a time T_4). Our idea is that, due to the visual stimulus in T_2, the subject will modify the exploration during T_4, thus reducing the number n of switching between (H) and (S), thus reducing T_e. Our hypothesis has been confirmed by experimental evidence, as shown in Fig. 6), where we show the number n of transitions (mean and standard deviation) obtained with the two protocols (MGF and MGF2) on a control group of 30 subjects. We have noticed that n strongly decreases in MGF^2.

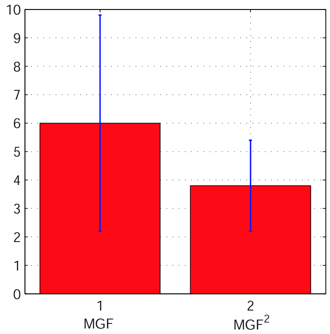
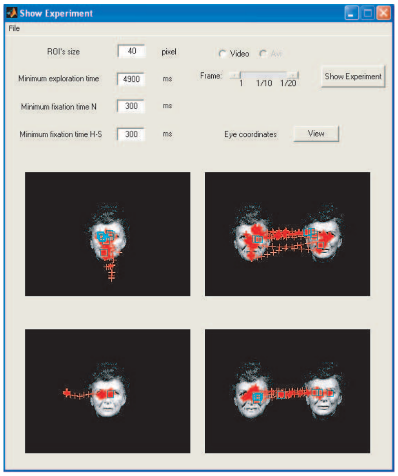


Fig. 6. Number of transitions n between (H) and (S) faces (mean and standard deviations) obtained experimentally using the MGF and MGF2 protocols. Over 150 experiments have been executed using 30 subjects.

Finally, note that the data acquired from the eye-tracker have been analyzed with a novel dedicated MATLAB software realized in our labs. It removes eye-blinks, extracts and visualizes regions of fixation and creates movies of the experiments (Fig. 7).



ROI's size 40 pixel

Minimum exploration time 4900 ms

Minimum fixation time N 300 ms

Minimum fixation time H-S 300 ms

Frame: 1 1/10 1/20

Eye coordinates

Fig. 7. The MATLAB interface aims at computing and visualizing the regions of attentions (boxes), creating movies of the experiments and many others.

IV. EXPERIMENTAL RESULTS

The experimental setup we used to study the influence of TMS in visual attention brain mechanisms towards happy and sad faces is that described in Sect. II. The visual stimulation has been realized using the MGF^2 protocol (Sect. III).

Two different experiments have been designed. In the first experiment, we studied the gaze behaviour of 30 subjects. In particular, we analyzed the exploration and used the fixation times. These were paramount to estimate the parameters T_1, T_2, T_3 and T_4 for the MGF^2 protocol. In the second and third experiment, we used the above parameters and studied the effects on the gaze behaviour under repetitive TMS (rTMS) in normal and depressed patients, respectively. Due to the novelty of our research, we decided in these first experiments to keep fixed the TMS coil over the left and right DLPFC (Dorso-Lateral Pre-Frontal Cortex) area, without using the robotic manipulator.

A. *Gaze behaviour*

When the neutral face (N) is shown for a period T_1, an exploration phase is initially performed by the subject. We experimentally observed interesting peculiarities about this phase, that can be roughly divided in:

- *Studying*: the subject's gaze scouts the face (N) observing all the features for a time T_1^{exp};
- *Fixation*: the subjects starts to fixate some facial features of particular interest for a period greater or equal than T_1^{fix} .

We visually stimulated 30 subjects using 12 different faces (for a total of 150 experiments) and we obtained that the average exploration time is T_1^{exp}=4.9 s, while the fixation time is T_1^{fix}=0.9 s. Consequently, the other periods have been chosen as T_2 =10 s, T_3 =3 s and T_4 =10 s.

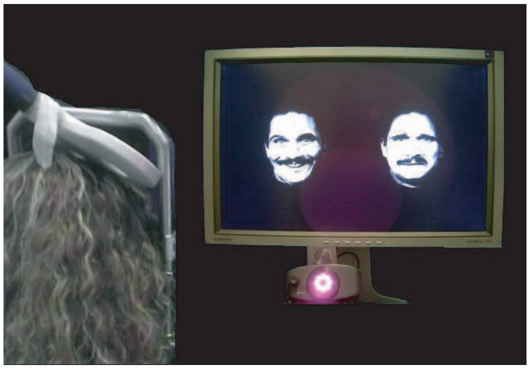


Fig. 8. Experimental session. A subject is placed in front of the PC display and stimulated using the MGF2 protocol. rTMS has been delivered on the dorso-lateral pre-frontal cortex according to the time instants $T_{1,\ldots,4}$.

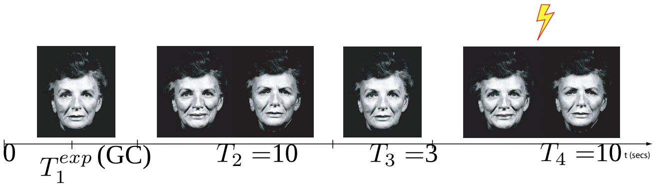


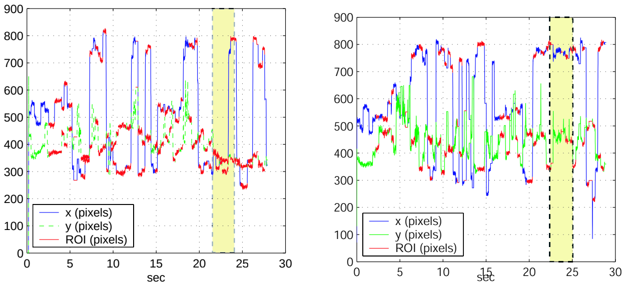
Fig. 9. Experimental results. The Memory Guided Filtering 2 protocol.

B. rTMS effects on visual attention

We here present some preliminary experiments obtained on 10 subjects. We adopted the MGF2 protocol with the time periods chosen as in Sect. IV-A and implemented the *gaze-contingent* algorithm [7] in ASTIDET in order to automatically switch to T_2 (Fig. 9) when a fixation was detected after T_1^{exp}. The use of gaze-contingent reduced, in many cases, the length of the experiment. Each subject has been stimulated in T_4 with rTMS (20 pulses at 10 Hz) after 5 s. We stimulated the dorsolateral pre-frontal cortex (DLPFC) [17] 1) *left* and 2) *right*. Other two control conditions were carried out: 3) *no rTMS stimulation* and 4) *sham rTMS*. Sham stimulation consists in positioning the coil perpendicularly to the head (thus no magnetic field is induced). However, in sham (differently to 3), the subject continues to hear the typical stimulation noise from TMS, which in some circumstances is per se able to change cognitive strategies [22].

Fig. 10(a) represents the x, y eye-coordinates motion for the *sham* stimulation delivered at 22 s. The highlighted box groups the whole duration of the stimulation. As can be seen, the eye scouts from one face to the other (spike in the x-coordinates). Instead, in Fig. 10(b), the subject has been stimulated using rTMS on DLPFC (right) at 23 s. As can be seen, the eye remains on the face he was pointing at the moment of rTMS (i.e., the happy in nearly 80% of cases) and continues to explore it by means of physiological microsaccades.

This interesting evidence, that has been observed in *all* the experiments, suggests that *active rTMS delivered on the DLPFC strongly reduces the number of transitions between the two presented faces*. There was no carry over effect after the end of stimulation. On the other hand, the number of transitions was not affected by sham rTMS, suggesting that the interference on the gaze control was not due to unspecific alerting effects which are known to affect other types of cognitive tasks as memory [19]. Moreover, it is unlikely that this effect was due to an interference on brain areas controlling eye movements: indeed, even during the rTMS-induced gaze permanence on the face, finalized explorative micro-saccades and vertical scanning eye movements on specific regions of interest (ROIs) of the face expression (i.e., eyes, nose, mouth) were preserved in the majority of subjects.

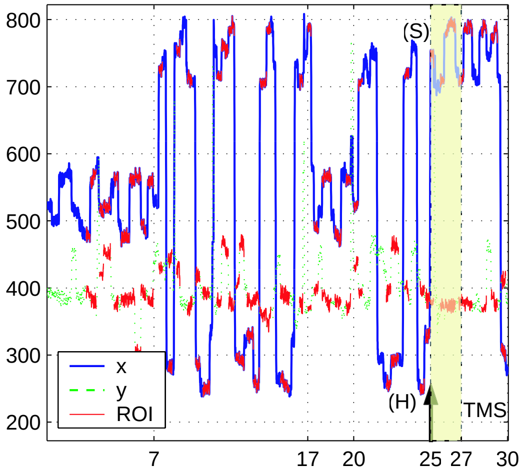


(a) (b)

Fig. 10. Experimental results. (a) Sham stimulation for 2 s. (gray square) (b) rTMS on DLPC right (gray square) 2 s.

C. HRI application in depression

As described in the Introduction, our human-robot interface aims at acting on the cognitive and emotional human system. Thus, according to Sect. II-B, we present here some



(a)

Fig. 11. Experimental results on depressed patient. At time $t = 23$ sec. the subject was looking at the happy face (H) (corresponding to the left side of the monitor). During the transcranial stimulation the depressed patient was deviated toward sad face (S) (corresponding to the right side of the monitor).

experiments obtained on a voluntary patient, A.C., 19 years old, who is affected by major depression. We have used the MGF^2 protocol with $T_1 = 7$ sec and without the gaze-contingent (this has been proven to be a reasonable time for a subject to memorize all facial features). We also used the same stimulation protocol than in Sect. IV-B. First of all, we have been impressed by the fact that the patient was always looking at sad face features (S), with minor attention to happiness (H)[1]. Second, and most important, we have noticed in all the experiments that, if the patient was not looking at (S) at the moment of stimulation then, during rTMS, his gaze was deviated towards (S) (e.g., see gray box in Fig. 11). Since the patient preferred to look always at the sad face (S), this experiment shows that our human-robot interface really acts of the cognitive and emotive behaviour. This can be addressed as an interesting results for future applicability of our interface to the rehabilitation in cognitive and emotional domains.

V. CONCLUSIONS

In this work we have presented a new kind of human-robot interface for active interaction with the *cognitive* and *emotional* human domains. The core HRI software is ASTIDET, which synchronizes the acquisition of data from ET and the stimulation pulses from TMS. ASTIDET allows also to load images that we decided to use as visual stimulation and shows them according to a new protocol, called MGF, for naturally stimulating one subject's emotions (the pictures represent facial expressions). Then, we presented preliminary experimental results that suggested how repetitive TMS strongly reduces the number of transitions between a shown pair of face pictures, consistently inducing the subject's gaze to remain within the face that was pointed at the moment in which rTMS was delivered. We propose that rTMS-induced gaze permanence on a given face may represent a reflection of the subject's empathy towards that face. We have made some experiments on a subject affected by depression and shown that our human-robot interface acts on the subject's cognitive and emotive status.

We are planning to perform experiments with a higher number of depressed patients and provide accurate statistical analysis. Future works will deal also with the automatic movement of TMS coil by means of the manipulator over specific brain areas: in this way, rTMS could be induced with more precision (clinical and behaviour data can be also used to this aim) and according to medical therapies.

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[1] A video of the patient's gaze showing his interest to sad features can be downloaded in the section "Video" in: http://sirslab.dii.unisi.it/medapp/HMI