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Applications in cochlear implants and avionic: Examples of how neurometric measurements of the human perception could help the choice of appropriate human-machine interaction solutions beyond behavioral data

Giulia Cartocci*[1,2], Anton Giulio Maglione[1,2], Dario Rossi[1,2], Enrica Modica[1,2], Paolo Malerba[3], Gianluca Borghini[1,2,4], Gianluca Di Flumeri[1,2,4], Pietro Aricò[1,2,4] and Fabio Babiloni[1,2]

[1]Sapienza University of Rome (Italy)
[2]BrainSigns srl (Italy)
[3]Cochlear srl (Italy)
[4]IRCCS Fondazione Santa Lucia (Italy)

ABSTRACT

The availability of indexes linked to distinct mental functions suggests their use in the evaluation of the cerebral impact of human machine interface or devices by measuring the induced cerebral activity. This approach could reveal additional information concerning the efficacy evaluation of the proposed device or interface, beyond the participants' behavioral and verbal reports. The mental workload index (frontal EEG power spectra increase in the theta band and simultaneous parietal EEG power spectra decrease in the alpha band) is an example of these indexes and in this study it was employed to identify the most appropriate cochlear implant processor in one postlingually deaf 43 years old male unilateral CI user. Results were compared with those obtained in another study involving the selection of the most appropriate devices in a helicopter cockpit. Data showed a statistical significant difference between sound processors (Freedom, CP810 and CP910) (F(2,180) = 3,046 p=0.05. In addition, the trials in which the Noise filter reduction function was adopted reported statistically significantly lower IWL values in comparison to the trials with No noise filter reduction use (F(1,90) = 8,027 p = 0,006). The evidences support the capability of identifying the devices eliciting less workload level. Such devices would free up user's cognitive resources that will be available for other additional tasks.

Keywords: *Cochlear implant, cerebral workload, deafness, word recognition, listening effort.*

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*Corresponding Author:
Giulia Cartocci
Dept. of Molecular Medicine, Sapienza University of Rome,
Piazzale Aldo Moro, 5, 00185, Rome, Italy.
E-mail: giulia.cartocci@uniroma1.it

1. Introduction

Nowadays, reliable indexes of cerebral activity are estimated from multichannel electroencephalographic recordings. Such indexes are linked to several distinct “mental states” such for instance the pleasantness of the perceived stimuli, through the Approach-Withdrawal index (Davidson, 1992) or the mental workload induced by cognitive tasks, through the increase of the power spectral density of the EEG collected from the frontal scalp areas (as reviewed in Borghini, Astolfi, Vecchiato, Mattia & Babiloni, 2014). The availability of different cerebral indexes linked to distinct mental functions related to appreciation or evaluation of the complexity of the perceived stimuli suggests that in a short future it will be possible to evaluate directly in this manner the cerebral impact of particular human machine interface or devices. This will be performed by measuring the cerebral activity induced by the interaction of participants with the particular devices or interfaces to be evaluated. This approach could reveal additional information related to the evaluation of the efficacy of the proposed device or interface when compared to the explicit verbal answers that the participants could provide after the interaction with the device. In fact, mental indexes related to the appreciation or the evaluation of the complexity of the perceived stimuli have a time resolution that allow to correlate more precisely the stimuli provided to the participant’s perception than the verbal summary provided at the end of the experience.

In the following of this paper, we would like to illustrate one case in which the evaluation of mental indexes during the participant’s experience with a particular cochlear devices. We draw such example from the choice of the most appropriate processor for the cochlear implant, but we compare such results with those obtained in another study involving the selection of the most appropriate combination of devices in the cockpit of an helicopter.

Bioengineers’ objective is very often represented by the developing of devices able to substitute or ameliorate lost or severely compromised functions of the human organs. In this scenario, cochlear implants represent one of the most successful example of devices able to replace the function of the Organ of Corti and restoring the transduction of the sound signal. A sound processor worn behind the ear or on the body captures sound and turns it into digital code. The sound processor transmits the digitally-coded sound through the coil on the outside of your head to the implant. The implant converts the digitally-coded sound into electrical impulses and sends them along the electrode array placed in the cochlea (the inner ear). The implant's electrodes stimulate the cochlea's hearing nerve, which then sends the impulses to the brain where they are interpreted as sound.

Thanks to technological developments and clinical rehabilitation optimization, performances expressed by cochlear implant users are continuously improving. To this end, scientific evidences report that fitting cochlear implants (CI) for optimal speech perception does not necessarily optimize listening effort, that may change between CI processing conditions for which speech intelligibility remains constant (Pals, Sarampalis & Baskent, 2013). The speech signal is recognized by the cognitive system of the listener and noise and distortion negatively affect the cognitive system when interpreting it. Therefore the auditory system must interact with the cognitive system for optimal signal decoding. Listening effort has been defined as the proportion of limited cognitive resources engaged in interpreting the incoming auditory signal, so the presence of noise or distortions in a speech signal thus increases cognitive demand and listening effort (Stenfelt & Rönnberg, 2009). The worth questions to be addressed is: "Despite good performances, how much cerebral effort is the participant experiencing during the listening?" and "How to determine the best device choice for each participant beyond the observation of behavioral performance?".

The use of neurophysiological measures for assisting the clinical evaluation of participants has been adopted in hearing disorders for instance for cochlear implant candidates (Campbell, Cardon & Sharma, 2011), CI users (Sharma, Campbell & Cardon, 2015) and tinnitus (Attanasio et al., 2013; Cartocci et al., 2011; Cartocci et al., 2012). Nowadays the choice of the most suitable device is performed on the collection of behavioral data, questionnaires and performance scores. For instance, in the case of helicopter pilots, there are no cognitive metrics for technologies comparison, so the selection relies on expert-supervision and questionnaire for subjective workload evaluation, such as the NASA-TLX (Hart & Staveland, 1988), are generally used for this purpose. In such scenario, the mental workload level could be estimated in three modalities: i) performance evaluation, ii) subjective questionnaire and iii) physiological measurement. The first modality doesn't provide any information about the requested user's workload, but estimates an indirect measure of it; the second modality is influenced by the participant's perception and interpretation of the workload level experienced. Due to its subjective nature, the workload perception in pilots is often inaccurate and many factors, including higher self-estimation and underestimation of difficulties, could lead to a poor reported judgment (Borghini et al., 2015). Concerning the third modality, it could provide more objective information about the user's mental workload, as it is directly estimated from the cerebral signals collected by electroencephalographic (EEG) recordings (Borghini, Astolfi, Vecchiato, Mattia & Babiloni, 2014). Also concerning devices for human functions substitution, such as cochlear implant, the choice of the most appropriate fitting is performed on the basis of speech intelligibility tests performances and on evaluations expressed by the participant and by clinicians. Similarly to Borghini and colleagues (2015) in the case of helicopter pilots, Pals, Sarampalis and Basken (2013) adopted the NASA-TLX for the subjective assessment of listening effort due to the execution of a listening task and two decision-making secondary tasks applying an auditory CI-simulation paradigm. NASA-TLX is a multidimensional scale that measures a range of aspects contributing to perceived workload: mental demand, physical demand, temporal demand, performance, effort, and frustration (Hart & Staveland, 1988). The total score is the weighted mean of the scores from the different dimensions. The weights are determined after the experiment by pairwise comparison. For all possible pairs of dimensions, the participants are asked to indicate which of two contributed most to the overall workload of the tasks. This procedure of weighting the ratings is designed to reduce inter-subject variability resulting from differences in individual interpretation of workload and its factors. Results presented in the study by Pals, Sarampalis and Basken (2013) suggested that, despite reaction times measures captured an improvement, or benefit, of increasing spectral resolution from six to eight spectral channels, the speech intelligibility task and the NASA TLX missed the detection of the improvement in the task execution. A very similar result of a lacking of detection capability has been reported by Borghini and colleague (2015) (Fig.1A) in the evaluation of the perceived mental workload among different visual conditions (Good Visual Environment, GVE; Marginal Visual Environment, MVE; Degraded Visual Environment, DVE) and avionic technologies (Head-Mounted Display, HMD; Head-Up Display, HUD) after the simulation of several flight scenarios in pilots.

A growing body of literature witnessed the EEG spectra modulation corresponding to the variation of the mental workload and to the allocation of mental effort (e.g. Klimesch, 1999), and in particular in relation to studies on pilots (Aricò et al., 2014; Berka et al., 2007; Lei & Roetting, 2011; Maglione et al., 2014a). Several studies also described the correlation of spectral power of the EEG with the complexity of the task that the user is performing. In fact, an increase of the frontal EEG power spectra in the theta band (4-7 Hz) and a simultaneous decrease in the parietal EEG power spectra in the alpha band (8-12 Hz) have been observed when the required mental workload increases (Borghini et al., 2014). Hearing impaired participants experience increased effort and/or stress during speech recognition in noisy conditions in comparison to normal hearing (NH) listeners (Asp et al., 2014; Caldwell & Nittrouer, 2013; Wendt, Dau & Hjortkjær, 2016). Recently, the evaluation of the mental workload index has been applied also at the study of the cochlear implanted children, with the aim of investigating IWL levels during a word recognition task varying different noise conditions (Cartocci et al., 2015). The authors of such study suggested a modulation of the IWL in different phases of the forced choice word recognition task: i) an increase in the IWL while expecting the listening of the word, during the most demanding noise condition for the participant; ii) a possible burnout expressed by IWL during the same noise condition, in the phase immediately preceding the choice execution. In the case of such study, the research was focused on the identification of the more challenging noise condition in the context of a word recognition task. However, another aspect worthy to be investigated is if different versions of cochlear implant devices elicit different measurable levels of mental workload. With this aim, it has been chosen to include in the study three processors versions, developed along less than 10 years and produced by the same company (Cochlear Ltd), so to maintain the same quality standard. In literature, comparisons among the selected sound processors have been performed on the base of traditional clinical outcomes: such as speech perception tests. For instance, evidences showed that performances obtained in word perception tests were significantly improved when using Nucleus 6 (CP910) in comparison to Nucleus 5 (CP810) both in adults (Mauger, Warren, Knight, Goorevich & Nel, 2014). Similar observations were made also on children CI recipients, but circumscribed at the speech in noise perception test (Plasmans et al., 2016).

In this framework, as before described the present study would like to investigate through neurometric performed by an EEG approach, the most suitable feature selection for devices conceived to operate in symbiosis with human in physiological perception conditions, such as cochlear implant.

2. Methods

The participant was a 43 years old male unilateral CI user, postlingually deaf (probably genetic etiology), implanted at 35 years old in his right side and not aided in his left ear. He was asked to perform a word recognition task in 3 noise conditions. The kind of noise used was babble noise and words were disyllabic; all audio stimuli were taken from a clinical standardized set (Turrini, Cutugno, Maturi, Prosser, Leoni & Arslan, 1993). The experimental conditions were: “No Noise” (NN), with the participant hearing words stimuli in quiet; “Noise without filter reduction” (NwoF) and Noise with filter reduction” (NF). All the auditory experimental conditions were tested using 3 different kind of processors: Freedom, CP810 and CP910 by Cochlear.

The NN condition was used only to verify the participant’s starting level of words comprehension so, reaching the 95% it will not be discussed anymore in the article.

The inclusion criterion was word comprehension rate of at least 80% at 65 dB and, that intensity was selected for stimuli delivery in the experiment. The signal to noise ratio (SNR) was +5 in all experimental conditions.

2.1 Cochlear Implant Features

The processors included in the testing were all produced by the same company (Cochlear Italia, Bologna, Italy), so to maintain the same quality standard in order of evaluating different processor versions developed along less than 10 years:

1. Freedom (2005): it uses one omni-directional microphone and a dual post-directional microphone. Both microphone systems help the recipient achieve enhanced directionality in front of them. Freedom presents different speech processing pro-grams with four optional functions. Two of these functions have been tested in the present work since their involvement in noise reduction strategy: Beam and ADRO. Beam allows to focus on the sounds coming from the direction in which the participant is looking, using a dynamic directionality. It can be used, for example when talking with someone in a crowd, with occurrence of distracting noise behind or beside the user. ADRO is the normal default directionality response; it makes automatic adjustments where there are large changes in sound between loud and soft. It is used, for example where there is much background noise: soft sounds are better detected, so that loud sounds are more comfortable and speech is clearer.
2. CP810 (2009): presenting speech processing programs with optional functions, among which ADRO (as Freedom) and Zoom, tested in the present study. Zoom provides fixed directionality in front of the participant. CP810 Sound Processor uses two separate omni-directional microphones; the output from the second micro-phone is electronically delayed and subtracted from the first

microphone output to provide more hearing towards the front of the recipient, so providing directionality.

3. CP910 (2013): it presents a dual-system microphone improved in comparison to the CP810, and a completely automatic processing of the sounds. Also for this sound processor ADRO function has been tested, and in addition the Background Noise Reduction (SNR-NR). The SNR-NR works by statistically analysing the incoming signal (irrespective of direction), and estimating the instantaneous signal to noise ratio (SNR) of the sound. It then retains signal segments with high SNRs, and strongly attenuates signals with low SNRs thereby making speech easier to hear in noisy condition. The SNR-NR attenuates constant background noises irrespective of their direction (Mauger, Arora & Dawson, 2012). This technology assesses the listening environment and detects the background noise level in each frequency channel. It then estimates the SNR in each channel for each analysis frame. The channels with poor SNRs indicative of background noise are attenuated, whereas channels with positive SNRs, typically dominated by speech, are retained.

Sarampalis, Kalluri, Edwards and Hafter,(2009) showed that hearing-aid-like noise reduction strategies can produce ameliorated performances on a secondary task, even when no improvement in speech intelligibility is seen. This finding implies that a hearing device feature, such as noise reduction, though it may be deemed not beneficial when assessed only with an intelligibility test, may instead be beneficial leading to a reduction in listening effort. Due to the suggested influence of the background noise on the listening effort of CI recipients, two filters features conditions were tested:

- No noise filter reduction use, that is the use of ADRO alone
- Noise filter reduction use, in other words the use of Beam, Zoom and SNR-NR for the Freedom, CP810 and CP910 respectively

2.2 Stimuli Setting

In all the experimental conditions noise and words stimuli were delivered by 1 front and 1 back loudspeakers, positioned 0° and +180° in relation to the participant. During the trials where it was present, the noise was emitted continuously.

Each experimental condition comprised 20 trials corresponding to 20 words, each trial lasting maximum 8 seconds and varying in length depending on the participant's response time. The word recognition task consisted in the listening of one word and then the participant was asked to verbally say only the just heard word. In case of uncertainty the participant was instructed to say whatever he thought to have heard.

2.3 EEG Acquisition and Analysis

A digital ambulatory monitoring system (Bemicro EBNeuro, Italy) was used to record EEG. Participants were sitting in a comfortable chair in a shielded room. For the acquisition a 19 channels cap was used. Electrodes were wet and placed according to the international 10-20 system (Fp1, Fp2, F7, F8, F3, F4, Fz, T3, T4, C3, C4, Cz, P7, P8, P3, P4, Pz, O1, O2). Signals were acquired with a sampling frequency of 256 Hz and collected simultaneously during the experiment. A 50- Hz notch filter was applied to remove the power interference. A ground and a reference electrode were placed on the forehead and the impedances were maintained below 10 (kΩ). The EEG recording was filtered with a band pass filter (2-30 Hz) and then the Independent Component Analysis (ICA) was used to manually remove artifacts and blink component from the traces by an experienced researcher. Successively EEG recordings were segmented into epochs of 1 second each, shifted of 0.25 seconds. The Power Spectrum Density (PSD) was calculated for each epoch and channels, observing the EEG PSD values in theta (4-8 Hz) and alpha (8-12 Hz) bands. The index of workload (IWL, Formula 1) was defined as the ratio between the averaged EEG PSD in theta band over the central frontal area (F7,F8,F3,F4,Fz) and the average value of EEG PSD in alpha band over the central parietal area (P7,P8,P3,P4,Pz) (Klimesch, 1999).

$$IWL = PSD(\theta F) / PSD(\alpha P) \qquad (1)$$

The IWL values were analysed by the repeated measures Analysis of Variance (ANOVA) in order to compare the different: kinds of processor (Freedom, CP810 and CP910) and the different noise filter conditions of the devices (No noise filter reduction and Noise filter reduction) during the task.

3. Results

3.1 Behavioral Results

Behavioral results were based on the number of correct responses (number of words correctly identified) within each trial expressed by the participant. Even without reporting a statistical significance (ANOVA $F(5,95)=1.341$ $p=0.254$) a higher percentage of correct responses was obtained in the Noise filter reduction application condition in comparison to the No noise filter reduction condition (Fig.1B). In particular, the condition in which the best score was obtained for both the Noise filter reduction and the No noise filter reduction is the CP910 sound processor adoption.

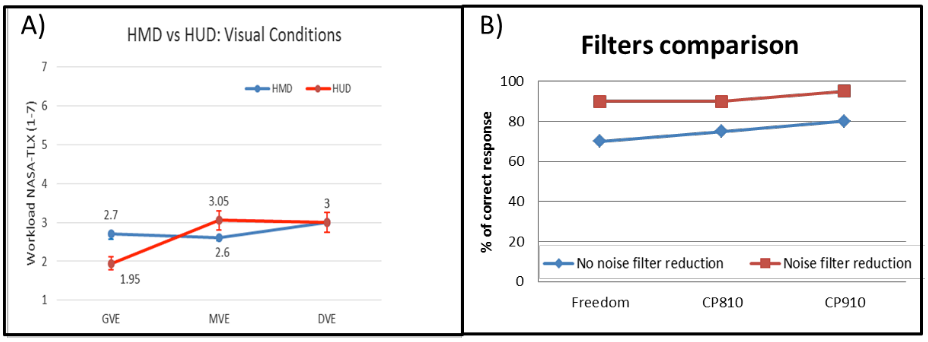

Figure 1. A) Behavioral scores reported in the comparison among different visual conditions in the helicopter pilots varying the avionic technology: *Head-Mounted Display* (HMD) and the *Head-Up Display* (HUD);
B) and among different processors varying the filter modality (without and with noise filter reduction). Part A) taken from Borghini and colleagues (2015).

3.2 EEG Results

Concerning EEG data, the comparison between the IWL values obtained during the testing of the three different kinds of sound processor (Freedom, CP810 and CP910) showed a statistical significant difference (F(2,180) = 3,046 p=0.05), with the lower value reported in the CP910 trial and the higher value in the Freedom trial (Fig.2B).

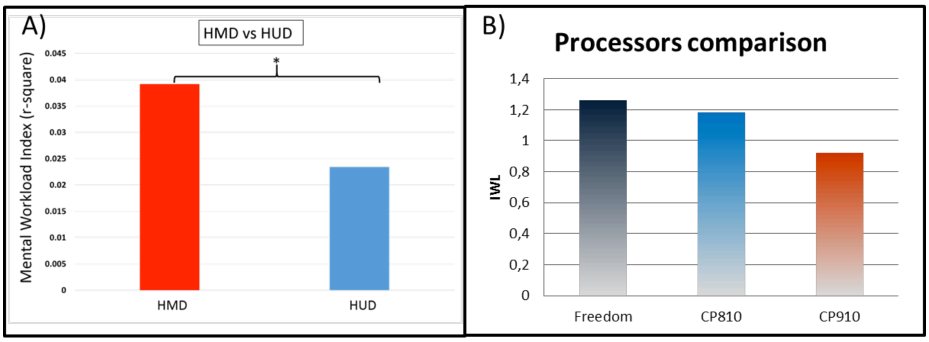

Figure 2. Workload index values reported in: the comparison between avionic technologies in helicopter pilots A), and between processor types in a cochlear implant recipient B). Part A) taken from Borghini and colleagues (2015).

Furthermore, the plotting of the behavioral data (Recognition) and the IWL values for the different sound processors highlighted lower IWL and higher % of word recognition for the CP910 processor trial (Fig.3). While in the Freedom and CP810 trials it has been obtained the same Recognition score but the higher IWL value for the Freedom processor.

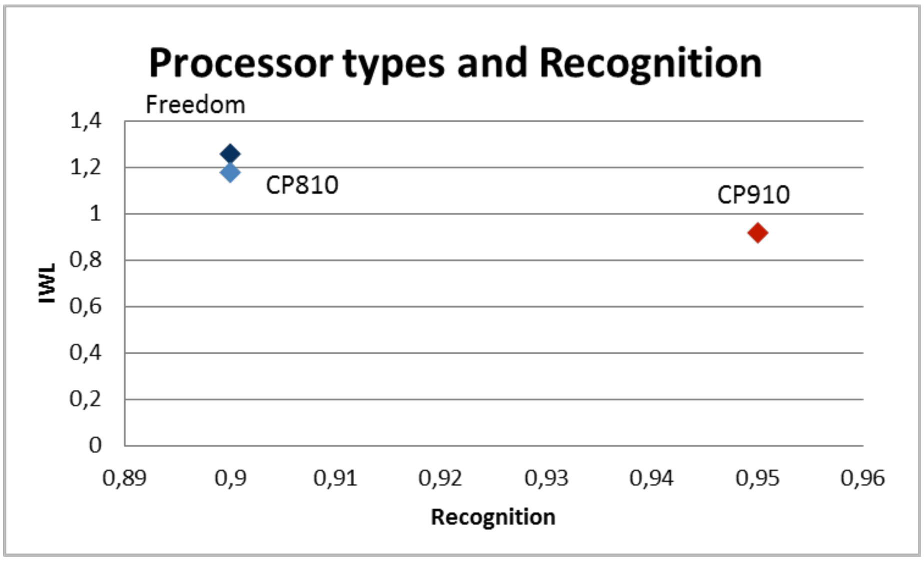

Figure 3. Workload index values plotted with the behavioral word recognition scores obtained by the participant using the different tested processors (Freedom, CP810 and CP910).

Considering the filters features (Fig.4), the trials in which the Noise filter reduction function was adopted reported statistically significantly lower IWL values in comparison to the trials with No noise filter reduction use (F (1,90) = 8,027 p = 0,006).

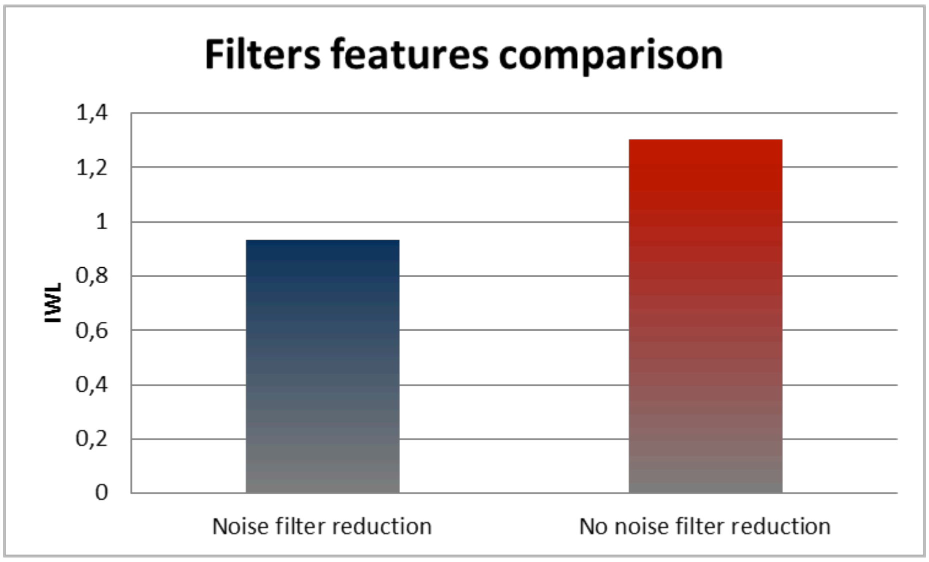

Figure 4. Workload index values reported in the comparison between the Noise filter reduction and the No noise filter reduction condition ($p<0.01$).

4. Discussion

Concerning behavioral data, as far as for the avionic technology testing example (Fig.1A), the NASA-TLX questionnaire didn't detect a significant difference among the trials (Fig.1B), so supporting the hypothesis of the needing of objective and not only subjective measures to describe the effort levels determined by a particular task execution (Borghini et al., 2015; Pals et al., 2013). Researchers hypothesize that the self-evaluation of listening effort, do not reflect the effort but the ease of use of a device (Feuerstein, 1992). Rubio, Diaz, Martin and Punte (2004) showed that the NASA TLX obtained the highest correlation with performance, possibly explaining the NASA TLX results accordance to the intelligibility results more closely and, like the intelligibility measures, are less sensitive to changes in listening effort (Pals et al., 2013). Furthermore, the issue of elevated listening effort is clinically extremely worthy; for instance, numerous Dutch CI users reported increased listening effort using a CI compared with the preimplantation condition (Van Hardeveld, 2010) and such optimization in the listening effort and in the measurement of it on clinical devices would be beneficial for these situations.

The possibility to measure, through neurometrics an indication of the level of listening effort in CI users has been approached by EEG studies using event related potentials (ERP), such in a very recent study by Finke, Büchner, Ruigendijk, Mejer and Sandmann (2016), who found a correlation between N2/N4 latencies and rated listening effort. Furthermore, beyond the effort level rating, the above mentioned research by Cartocci et al. (2015) showed an increase of IWL values in cochlear implanted children when tested in the most demanding noise condition for them. The results presented in this article shift the focus of the listening effort estimation from the noise condition matter to the best choice of the kind of device to be adopted matter, in order to enable users to face different auditory conditions. With regards to the IWL values obtained by the experimental participant while adopting each of the different sound processors, it has been attained the lower workload level in correspondence of the use of the CP910 use. In a very recent study investigating the workload levels induced by an auditory forced choice word recognition task in adult unilateral cochlear implant users (Maglione et al., 2016), similar results have been obtained. Authors found evidence of a statistical significance of the interaction between kinds of processors and noise filter reduction use, with a trend of lower IWL values in correspondence of the use of the CP910 processors.

Some authors hypothesize that Noise Reduction (NR) features in hearing devices reduce listening effort and frees up cognitive resources for other tasks (Sarampalis et al., 2009). Hafter and Schlauch (1992) proposed that NR algorithms in the processor do not improve speech reception thresholds (SRTs) in the laboratory because they perform a function similar to that of the listeners' auditory and cognitive systems and, as such, do not improve speech understanding. The same authors suggested that the NR, in doing for them what they could do for themselves, it lightens their cognitive load. From this perspective, NR might not affect the SRT but may release attentional resources to be used for other, simultaneous tasks. Although this reduction in cognitive load might not affect performance in traditional speech tests conducted in the laboratory or clinic, it could be important in more natural settings, where multitasking is the norm and cognitive demands are greater. The concept of identifying devices allowing to save cognitive resources for secondary tasks execution or for coping with more challenging than normal situations appears of immediate comprehension when speaking of potentially dangerous situations as for helicopter pilots (Fig.2A) (Borghini et al., 2015), but it is also extremely worthy for facing everyday challenging situations such as noisy environments for cochlear implanted participants (Fig.2B). This consideration acquires a clear evidence just thinking for example at the requirements for the sustained attention that children have to generate during their learning processes in the early scholar period of their life. This issue is also supported by the 2 to 5 times greater risk of clinically significant deficits in preschoolers and school-aged children with CI in comparison to NH children, for instance in the areas of comprehension and conceptual learning (3.56 and 6.25), attention (3.38 and 3.13) (Kronenberger, Beer, Castellanos, Pisoni & Miyamoto, 2014). Other scientific evidences come from the study of Gosselin and Gagné (2011) that showed an increased effort level in older in comparison to young adults in recognizing speech in noise.

Finally, the sum of the present results, as long as the scientific evidences reported in pilots and drivers, strongly suggest the usefulness of mental workload estimation for the choice of the most proper device to be employed in symbiosis with humans for physiological functions substitution. This single case study has the obvious limitation to be an investigatory first research, needing an upgrade on a congruent sample population. However the reported observations are consistent with the known behavior of the cerebral workload as estimated by the EEG usually applied in sensory and cognitive tasks quite different than those employed here in a more clinical context (Aricò et al. 2014; Aricò et al., 2016; Di Flumeri et al., 2016; Klimesch, 1999; Maglione et al., 2014b; Pichiorri et al., 2011).

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