

Beyond Accuracy: User Experience Matters in the Comparison of Two EEG Headsets for BCI

S. Petrinotti¹, A. Bigioni^{1,3}, V. Caracci^{1,2,3}, S. Boesso¹, J. Toppi^{1,2}, F. Cincotti^{1,2}, D. Mattia¹, A. Riccio¹

¹ Neuroelectrical Imaging and BCI Laboratory, Fondazione Santa Lucia IRCCS, Rome, Italy

²Dep. of Computer, Control and Management Engineering, Sapienza University of Rome, Italy

³Fondazione Neurone Onlus, Rome, Italy

E-mail: s.petrinotti@hsantalucia.it

ABSTRACT: Brain-Computer Interfaces (BCIs) are a promising Assistive Technology (AT) for individuals with severe motor impairments, enabling communication and interaction through neural activity without requiring muscular control. However, their integration into everyday assistive services remains limited, partly due to usability issues related to EEG acquisition devices. In particular, the comfort and acceptability of EEG headsets are key factors for long-term adoption.

This study compared users' subjective experience with two EEG headsets during a P300-based BCI spelling task: a gel-based cap (EasyCap), commonly used in laboratory and clinical settings, and a mobile semi-dry system (X.on) designed for out-of-lab applications. Ten healthy volunteers completed two sessions, performing the same task with each headset. After each session, participants filled out a questionnaire assessing satisfaction with headset, along with Visual Analogue Scales (VAS) evaluating perceived physical discomfort. Results showed higher overall satisfaction with the semi-dry headset, suggesting greater suitability for everyday BCI communication.

INTRODUCTION

Damage or dysfunction affecting the nervous system can severely impair motor function, limiting communication and interaction with the environment and reducing quality of life [1, 2].

Assistive Technologies (AT) have evolved to support communication and interaction for individuals with motor impairments through alternative input devices (e.g., eye-trackers, switches, alternative keyboards) and adaptive software solutions [1 - 4].

Despite advances in AT, individuals with severe motor impairments still face barriers to access. Brain-Computer Interfaces (BCIs) offer an alternative by translating neural activity into control signals without

requiring muscular output [2, 4, 5].

Among the different types of BCI systems, a subset is designed for communication and relies on the P300 event-related potential [1, 2, 6]. These systems typically operate according to a visual oddball paradigm, in which the user focuses attention on a target item displayed on a screen without performing any physical movement. The target appears as a rare stimulus among frequent non-target stimuli and elicits a P300 component in the EEG signal. By detecting this response across successive stimulus presentations, the system can infer the attended item, allowing the user's selection to be identified and used to enable communication or control external devices through brain activity [7].

Despite the growing body of research on BCIs, the integration of these devices into everyday assistive technology services is still limited. One of the main challenges is that most systems remain confined to laboratory settings, requiring specialized expertise for setup and operation. To fully realize their potential, BCIs need to be optimized for daily use, becoming more portable, easier to use, and suitable for home and everyday living environments [1, 2].

To achieve this goal, a User-Centered Design (UCD) approach is essential, ensuring that development is guided not only by technical performance but also by user experience factors such as comfort, usability, and satisfaction, which are crucial for system acceptance [8]. One of the key components that can influence the usability and acceptability of a BCI system is the EEG acquisition device worn by the user. The comfort, weight, fit, and overall experience of wearing the headset can significantly affect both performance and motivation to use it. A variety of EEG headsets are currently available, differing in their montage, number and type of electrodes, and acquisition technology. Based on the method of contact with the scalp, it is possible to distinguish between *gel-based*, *dry* and *semi-dry* headsets [9 - 14]. The first ones, also known as *wet* systems, represent the standard in neuroscience

and clinical research due to the high quality and stability of the signal they provide, but require a relatively long setup time and the need to wash hair, which influence their use in everyday contexts [9 - 11]. Dry headsets, in contrast, do not show this constraint, but they can cause physical discomfort due to the pressure of pin electrodes on the scalp [12, 13]. An intermediate category consisting of semi-dry systems, based on water or saline solution, represents a compromise between feasibility and signal reliability: they are quick to apply and do not leave any residues in the hair [10, 11, 14].

Furthermore, in order to incorporate the user's point of view, it is important to highlight that comfort and physical well-being are crucial factors for the prolonged use of EEG headsets: dry systems with pin electrodes often cause significant discomfort or pain over time, leading to headaches and user fatigue [9, 11, 12, 13]. User preferences are also strongly influenced by aesthetics and design. Gel-based EEG caps are often not appreciated, while modern and discreet designs are preferred [11, 13]. Headsets with electrodes positioned on the mastoids or around the ears are especially appreciated for being less noticeable [15]. Moreover, users tend to prefer headsets that are easy to use and quick to set up. Wet systems, with their slow preparation and the need to wash hair after each session, are less appealing for everyday or home use. In contrast, dry and semi-dry systems are preferred because they can be put on autonomously, without technical assistance, making them more practical and user-friendly for daily use [9, 13, 15].

Nonetheless, in this context, it is important to also consider the accuracy of BCI performance, that is to say the success rate of correctly classified user intentions during BCI operations. Most of the literature on EEG-based BCIs focuses on gel-based systems, which have been extensively studied in terms of signal quality and classification accuracy. However, some studies directly compare wet, dry, and semi-dry headsets, highlighting some differences in performance: dry EEG systems seems to exhibit lower accuracy compared to gel-based systems, with gel electrodes consistently providing more reliable classification performance [11, 15]. Furthermore, when evaluating signal quality, gel-based systems appear to maintain their superiority, exhibiting better signal-to-noise ratios [16]. Thus, the focus should be on achieving an optimal trade-off between BCI performance and user preference.

This study compares two types of EEG headsets, a gel-based cap widely used in clinical and research settings, and a mobile semi-dry system intended for use outside the laboratory, to control a P300-based BCI for communication. Both classification accuracy and user satisfaction are evaluated. The ultimate aim is to identify which system provides the best balance between BCI performance and user satisfaction, and is therefore better suited for integration into AT

solutions.

MATERIALS AND METHODS

Participants

Ten healthy volunteers participated in the study (mean age $\pm$ sd = 28.8 ± 4.3 ; 3 males and 7 females). According to the inclusion criteria, all participants were over 18 years of age and reported no history of neurological or psychiatric disorders. All research was conducted in accordance with the principles embodied in the Declaration of Helsinki. The study protocol was approved by the Independent Ethics Committee of Fondazione Santa Lucia in Rome.

Each participant completed two experimental sessions on the same day, separated by an interval of approximately 30 minutes, resulting in a total experiment duration of about 2 hours and half. The order of the sessions was counterbalanced across participants.

EEG acquisition

EEG signals were recorded to compare the performance of two different headsets during a P300-based BCI spelling task. In one session, participants wore an *EasyCap EEG headset* (Brain Products) with active gel electrodes, connected to a LiveAmp amplifier. A 12-channel montage was used (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, PO7, PO8, Oz), with reference and ground placed on the right earlobe. Although EEG activity was recorded from all 12 channels, only signals from 8 channels (Fz, Cz, P3, Pz, P4, PO7, PO8, Oz) were used for the online task. These channels correspond to the well-established *8-channel montage* widely employed in the literature for P300-based BCIs [17]. While signals from all 12 channels were recorded, only these 8 channels were transmitted to the BCI2000 software, and the classifier was trained using features derived exclusively from these channels [17]. In the other session, participants performed the same task using the *X.on EEG headset* (Brain Products), equipped with passive semi-dry electrodes in a 7-channel montage (F3, F4, C3, Cz, C4, P3, P4), with reference and ground on the right earlobe. The amplifier was integrated into the headset.

To ensure comparable conditions between the two montage types, EEG cap placement was performed by the same operator for all participants and across all sessions. The operator had no prior experience with either montage procedure, thereby ensuring an equivalent level of expertise for both setups. As no technicians with extensive experience in both cap types were available, an operator with no prior experience with either system was selected. Furthermore, the same setup procedure was adopted for both montages, consisting of skin preparation with alcohol cleansing in order to reduce impedance, cap positioning, and application of conductive gel or saline solution to facilitate electrical conduction between the scalp and the electrodes.

EEG headset design

From an aesthetic point of view, the two headsets are different. The EasyCap is made of fabric and has a fixed size, equipped with a chin strap for secure fastening. In addition to the fabric headset, an earclip is provided for ground and reference. The connections are made via cables to a central connection unit, which must subsequently be connected to the amplifier for EEG signal recording. Conversely, the X.on features a rigid structure composed of multiple arms, includes an adaptable frontal strap, and is adjustable for head circumferences between 54 and 60 cm, with an earclip also present for ground and reference. It integrates sponge electrodes and a built-in amplifier, so that no cables are needed between the headset and the external amplifier. Both the headsets are shown in Fig. 1.

P300 spelling task

As mentioned above, the spelling task was implemented using the BCI2000 platform [18]. Participants were seated approximately 60 cm from a computer monitor displaying a 5 x 6 matrix of 30 alphabetic and control characters. Rows and columns of the matrix were intensified in random order. Participants were instructed to focus their attention on a target letter indicated on the screen and to silently count the number of times it was highlighted. Each letter selection consisted of 8 row-column stimulation sequences, corresponding to 16 total intensifications. Stimulus duration was 120 ms and the inter-stimulus interval was 120 ms, resulting in a stimulus onset asynchrony (SOA) of 240 ms.

Experimental procedure

Each session consisted of nine runs. First, participants performed four runs of calibration, during which they were shown five-letter words (BACIO, POSTO, METRO, ZEBRA) verbally indicated before each run, with no feedback provided. EEG data from these runs were used to train the BCI classifier via Stepwise Linear Discriminant Analysis (SWLDA), which selects the most relevant features of the EEG signal and builds a linear model to discriminate between target and non-target responses, i.e., to correctly identify the letter the participant is intending to select [17].

Participants then completed five copy-mode runs which followed a structure similar the calibration runs and included online feedback, which was provided through the trained classifier parameters, enabling real-time classification. The words used in this phase were DANZA, GUSTO, MENTE, VIOLA and FIORE.

All the words employed were commonly used words selected from an Italian dictionary and chosen to cover most of the orthographic matrix.



Figure 1: Image of EasyCap (on the left), with the earclip (a) and the LiveAmp amplifier (b) and X.on (on the right), with the earclip (c), sponges (e) and their holders (d).

User perspective assessment

At the end of each session, the participants' subjective experience of the EEG headset used for the task was assessed.

A short questionnaire inspired by the extended Quebec User Evaluation of Satisfaction with assistive Technology ("extended QUEST 2.0") used in Zickler et al., [19] was administered to evaluate satisfaction regarding headset comfort, dimensions, weight, and aesthetic design. Each item was rated on a 5-point Likert scale ranging from 1 ("not satisfied at all") to 5 ("very satisfied").

To further investigate physical discomfort, three Visual Analogue Scales (VAS) adapted from Berger et al. [20] were administered to measure perceived pressure, perceived discomfort and perceived pain, each rated on a scale from 0 (none) to 10 (maximum). All subjective measures were administered by a trained psychologist. To allow the participant to provide an evaluation of the headset's aesthetic design, a mirror was placed in front of them during the headset setup and they were instructed to pay attention to their own image while wearing the headset. The mirror was removed during the task to avoid distractions and was then reintroduced at the end of the session for the administration of questionnaire and VAS.

Statistical analysis

For each participant and each headset, the following subjective indices were extracted from the questionnaire and VAS: *comfort satisfaction*, *dimensions satisfaction*, *weight satisfaction*, *aesthetic design satisfaction*, *overall satisfaction* (calculated as the mean of the four previous scores), *perceived pressure*, *perceived discomfort*, *perceived pain*, and *overall perceived discomfort* (calculated as the mean of the three previous scores).

In addition to these subjective measures, *accuracy* was extracted, calculated as the ratio of correctly selected letters to the total number of selections in the copy-mode phase. Additional performance metrics were also

evaluated during the experiment and will be reported in a separate paper related to the same experimental protocol (Caracci et al., “Evaluating the impact of electrode type and montage on classification performance in assistive P300-based BCIs”, submitted). The present work specifically focuses on the participants’ subjective evaluation.

Differences between the two headsets were then assessed for each index using a two-tailed Wilcoxon signed-rank test. The significance level was set at $\alpha = 0.05$. Then, multiple comparisons were controlled using the Benjamini–Hochberg false discovery rate (FDR) correction. All statistical analyses were conducted using the software *Statistica*.

RESULTS

The primary outcome of interest was the accuracy achieved with the two headsets. It differed significantly between the two systems, with better performance for the EasyCap (p-value = 0.008; results of all the Wilcoxon tests were reported in Tab. 1). The median accuracy was 98 % for the gel-based headset and about 85 % for the semi-dry system, as shown in Fig. 2.

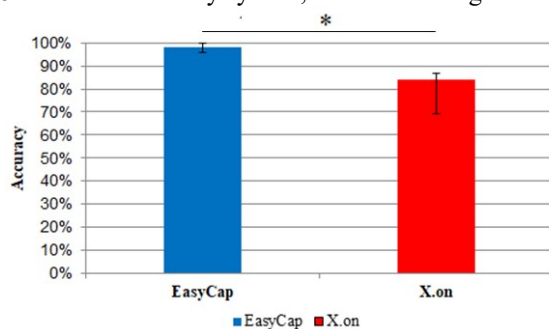


Figure 2: The figure shows the median values of the accuracy distributions for performances obtained with EasyCap (in blue) and with X.on (in red). Bars represents the median values, while error bars indicate the interquartile range (IQR). * denotes significant differences between the conditions ($p < 0.05$).

The results of the subjective assessment obtained through the questionnaire inspired by the extended QUEST 2.0 revealed a statistically significant difference in the overall satisfaction between the two conditions. As shown in Fig. 3a, participants reported significantly higher overall satisfaction (p-value = 0.005) for the X.on (median 4.5, IQR 4.5 - 4.75) compared to the EasyCap (median 3.38, IQR 3 - 3.5). A more detailed analysis showed that comfort satisfaction, weight satisfaction, and aesthetic design satisfaction were also significantly higher for the X.on (comfort: median 5, IQR 4 - 5 vs. median 3, IQR 3 - 3, p-value = 0.008; weight: median 5, IQR 5 - 5 vs. median 4, IQR 4 - 4.75, p-value = 0.028; aesthetic design: median 4.5, IQR 4 - 5 vs. median 2, IQR 2 - 2, p-value = 0.005). The test revealed no significant differences for dimensions satisfaction between the two conditions (median 4, IQR 4 - 5 vs. median 4, IQR 3.25 - 4.75, p-value = 0.286).

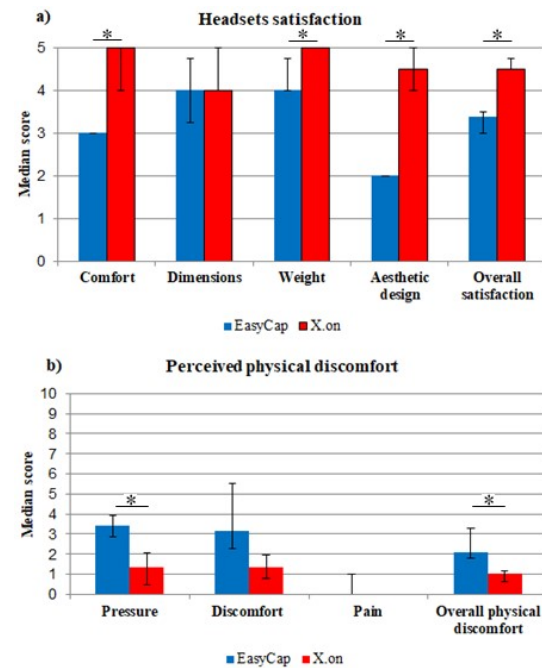


Figure 3: a) Median scores for the items assessing participants’ satisfaction with the two headsets in terms of comfort, dimensions, weight, aesthetic design and overall satisfaction (calculated as the mean of the four item scores). Each item was rated on a scale from 1 to 5. b) Median scores for the VAS assessing perceived pressure, perceived discomfort, and perceived pain (0 - 10 scale). An overall physical discomfort measure (calculated as the mean of the three VAS measures) was also reported. In both a) and b), blue and red bars represent the median scores for the EasyCap and X.on, respectively, with error bars showing the interquartile range. * denotes significant differences between the conditions ($p < 0.05$).

Complementing these quantitative ratings, participants’ qualitative comments on the questionnaire items provided a qualitative assessment of their satisfaction with the two headsets.

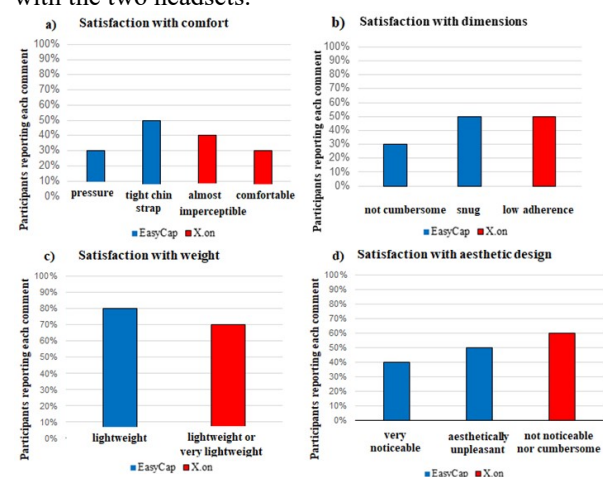


Figure 4: The figure shows participants’ most frequent comments to questionnaire items and corresponding percentages for each headset (blue for EasyCap and red for X.on). Each of the four panels presents a different aspect: a) comfort, b) dimensions, c) weight and d) aesthetic design. The bars indicate the proportion of participants reporting each comment.

As illustrated in Fig. 4, qualitative feedback revealed a generally more positive perception of the *X.on*, particularly in terms of comfort and aesthetic design. Participants frequently described it as comfortable and less noticeable, whereas the *EasyCap* was more often associated with tightness, perceived pressure, and unfavorable aesthetic impressions.

With regard to the results of the VAS, which rated perceived physical discomfort, they are shown in Fig. 3b. The overall discomfort score was significantly different between the two headsets, with higher values reported for EasyCap compared to X.on (median 2.08, IQR 1.78 - 3.31 vs. median 1.03, IQR 0.75 - 1.15, p-value = 0.005).

When examining the individual components, statistically significant differences were also observed for perceived pressure and perceived discomfort, both reported as higher for the EasyCap (pressure: median 3.40, IQR 2.85 - 3.95 vs. median 1.35, IQR 0.45 - 2.08, p-value = 0.005; discomfort: median 3.15, IQR 2.30 - 5.53 vs. median = 1.35, IQR 0.78 - 1.98, p-value = 0.041). However, the effect observed for discomfort did not remain statistically significant after correction for multiple comparisons. No significant differences were found for perceived pain (median 0, IQR 0 - 1 vs. median 0, IQR 0 - 0, p-value = 0.178).

Table 1. Wilcoxon signed-rank test results (Z statistics and p-values, Benjamini-Hochberg corrected).

Variable	Z	P-value	Significant (after Benjamini-Hochberg)
Accuracy	2.7	0.008	significant
Comfort	2.7	0.008	significant
Dimensions	1.1	0.286	not significant
Weight	2.2	0.028	significant
Aesthetic design	2.8	0.005	significant
Overall satisfaction	2.8	0.005	significant
Pressure	2.8	0.005	significant
Discomfort	2.0	0.041	not significant
Pain	1.3	0.178	not significant
Overall physical discomfort	2.8	0.005	significant

DISCUSSION

The present study aimed to determine whether there were differences in users' subjective experience between two EEG headset - a gel-based cap commonly employed in clinical and research environments, and a novel mobile semi-dry headset, designed for out-of-lab applications - during the same task, and to identify the specific factors underlying any observed differences.

Results from the accuracy analyses indicated that the EasyCap was more effective than the X.on. Specifically, the median accuracy was 98 % for EasyCap and about 85 % for X.on. While the latter performed significantly lower than the former, its mean accuracy remained well above 70 %, a threshold previously identified as sufficient for effective communication [21]. This finding suggests that, from a purely effectiveness-driven perspective, both systems could support functional BCI use, even though one clearly outperforms the other.

However, when considering the participants' subjective experience, a different picture emerged. Overall satisfaction, comfort, weight and aesthetic design were consistently rated higher for the X.on. Participants described it as lightweight, almost imperceptible, and visually unobtrusive, whereas EasyCap was frequently associated with excessive tightness, perceived pressure, and less favorable aesthetic impressions. Perceived physical discomfort was also significantly higher for EasyCap, particularly regarding pressure and general discomfort. These qualitative and quantitative insights highlight that user experience does not always align with measures of device effectiveness: a headset can be highly accurate yet cause discomfort or dissatisfaction, potentially limiting its practical usability. This points to the crucial role of user feedback in the optimization of BCI systems, to ensure that devices are not only effective but also acceptable and comfortable for daily use. To promote device acceptance, encourage frequent use in daily life, and prevent withdrawal, it is essential to consider both system effectiveness and user satisfaction during implementation. Adopting a BCI device that may sacrifice a modest amount of accuracy -still remaining above the communication threshold - to provide superior comfort and overall satisfaction, may ultimately result in higher usage rates compared to a highly effective device that is uncomfortable or poorly received by users.

The present study confirms previous literature indicating a user preference for EEG headsets that do not use conductive gel. The study by Hinrichs and colleagues highlights a clear user preference for EEG systems that do not use conductive gel compared to gel-based systems: 74% of participants preferred the gel-free system, whereas only 10% favored the gel-based one [9]. Even during longer recording sessions (up to 60 minutes), the gel-free system was rated as more comfortable [9]. The main reasons for this preference included the absence of conductive gel, which eliminates the need to wash the hair after use, the absence of a chin strap, which was perceived as uncomfortable in the gel-based system, and greater freedom of movement compared to wired setups. In addition, the gel-free system was positively evaluated in terms of usability, with most participants reporting that they would be able to wear the headset independently without technical assistance [9].

In any case, what appears to most strongly drive user preferences is the visual appearance of the device. Gel-based EEG caps were often rated negatively, being perceived as unattractive and overly conspicuous [11, 13]. Discreet designs are generally preferred, as they are better able to accommodate individual preferences and avoid drawing excessive attention in public settings [11, 13, 15].

All of these factors should be carefully considered when implementing a BCI device to ensure both effective performance and user acceptance.

CONCLUSION

The present study demonstrates that a semi-dry headset, designed for out-of-lab use, is significantly preferred over a gel-based research cap in terms of comfort, weight, aesthetics, and reduced physical discomfort. These results suggest that consideration of user-centered factors, including ergonomic and perceptual aspects (while maintaining a focus on effectiveness), is essential for promoting the practical adoption and sustained use of BCIs for individuals with severe motor disabilities.

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