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How to cite

WINDEL, Fabienne et al. Computer vision-based algorithm to sUppoRt coRrect electrode placemeNT (CURRENT) for home-based electric non-invasive brain stimulation. In: Clinical neurophysiology, 2023, vol. 153, p. 57–67. doi: 10.1016/j.clinph.2023.06.009

This publication URL: https://archive-ouverte.unige.ch/unige:172098

Publication DOI: 10.1016/j.clinph.2023.06.009

Clinical Neurophysiology 153 (2023) 57–67

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Computer vision-based algorithm to sUppoRt coRrect electrode placemeNT (*CURRENT*) for home-based electric non-invasive brain stimulation

Fabienne Windel [a,b], Rémy Marc M. Gardier [c], Gaspard Fourchard [a,b], Roser Viñals [c], Daphne Bavelier [d], Frank Johannes Padberg [e,f], Elmars Rancans [g,h], Omer Bonne [i], Mor Nahum [j], Jean-Philippe Thiran [c,k], Takuya Morishita [a,b,†], Friedhelm Christoph Hummel [a,b,l,†,*]

[a] *Defitech Chair of Clinical Neuroengineering, Neuro-X Institute (INX) and Brain Mind Institute (BMI), École Polytechnique Fédérale de Lausanne (EPFL), Geneva, Switzerland*
[b] *Defitech Chair of Clinical Neuroengineering, Neuro-X Institute (INX) and Brain Mind Institute (BMI), EPFL Valais, Sion, Switzerland*
[c] *Signal Processing Laboratory 5 (LTS5), School of Engineering, EPFL, Lausanne, Switzerland*
[d] *Department of Psychology and Educational Sciences, University of Geneva, Geneva, Switzerland*
[e] *Department of Psychiatry and Psychotherapy, University Hospital, LMU Munich, Germany*
[f] *NeuroImaging Core Unit Munich (NICUM), University Hospital, LMU Munich, Germany*
[g] *Department of Psychiatry and Narcology, Riga Stradins University, Riga, Latvia*
[h] *Riga Centre of Psychiatry and Addiction Disorders, Riga, Latvia*
[i] *Hadassah Medical Center, Jerusalem, Israel*
[j] *School of Occupational Therapy, Faculty of Medicine, The Hebrew University, Jerusalem, Israel*
[k] *Radiology Department, Centre Hospitalier Universitaire Vaudois and University of Lausanne, Lausanne, Switzerland*
[l] *Clinical Neuroscience, University of Geneva Medical School, Geneva, Switzerland*

HIGHLIGHTS

- Home-based NIBS is a promising new treatment strategy for neuro-psychiatric pathologies ensuring frequent stimulation exposure.
- There are currently no solutions to direct and monitor correct electrode placement for self-application.
- We propose an easy-to-use, digital electrode placement tool that marks an important step to improve home-based set-ups.

ARTICLE INFO

Article history:
Accepted 7 June 2023
Available online 4 July 2023

Keywords:
Home-based non-invasive brain stimulation
tES
Electrode localization algorithm
Real-time feedback
Monitoring
Computer vision

ABSTRACT

Objective: Home-based non-invasive brain stimulation (NIBS) has been suggested as an adjunct treatment strategy for neuro-psychiatric disorders. There are currently no available solutions to direct and monitor correct placement of the stimulation electrodes. To address this issue, we propose an easy-to-use digital tool to support patients for self-application.
Methods: We recruited 36 healthy participants and compared their cap placement performance with the one of a NIBS-expert investigator. We tested participants' placement accuracy with instructions before (*Pre*) and after the investigator's placement (*Post*), as well as participants using the support tool (*CURRENT*). User experience (UX) and confidence were further evaluated.
Results: Permutation tests demonstrated a smaller deviation within the *CURRENT* compared with *Pre* cap placement ($p = 0.02$). Subjective evaluation of ease of use and usefulness of the tool were vastly positive (8.04 out of 10). *CURRENT* decreased the variability of performance, ensured placement within the

Abbreviations: CURRENT, Computer vision-based algorithm to sUppoRt coRrect Electrode placement; MDD, Major Depressive Disorder; MMSE, Mini-Mental State Examination; MRI, Magnetic Resonance Imaging; NIBS, Non-Invasive Brain Stimulation; SD, Standard Deviation; tACS, transcranial Alternating Current Stimulation; tDCS, transcranial Direct Current Stimulation; tES, transcranial Electrical Stimulation; UX, User eXperience; VAS, Visual Analogue Scale.

* Corresponding author at: Defitech Chair of Clinical Neuroengineering, Neuro-X Institute (INX) and Brain Mind Institute (BMI), École Polytechnique Fédérale de Lausanne (EPFL), Chemin des Mînes 9, 1202 Geneva, EPFL Valais, Clinique Romande de Réadaptation, Av. Grand-Champsec 90, CH-1951 Sion.
E-mail address: friedhelm.hummel@epfl.ch (F.C. Hummel).
† These authors have contributed equally to this work.

https://doi.org/10.1016/j.clinph.2023.06.009

suggested maximum of deviation (10 mm) and supported confidence of correct placement.
Conclusions: This study supports the usability of this novel technology for correct electrode placement during self-application in home-based settings.
Significance: CURRENT provides an exciting opportunity to promote home-based, self-applied NIBS as a safe, high-frequency treatment strategy that can be well integrated in patients' daily lives.

1. Introduction

Alongside conventional methods, non-invasive brain stimulation (NIBS) has been proposed and used as a valuable addition to the treatment of psychiatric and neurological diseases (Lefaucheur et al., 2017, Brunoni et al., 2012, Hummel and Cohen, 2006, Palm et al., 2014, Draaisma et al., 2020, Menardi et al., 2022). One of the most frequently utilised techniques, because of its low cost, excellent safety profile and good tolerability is transcranial direct current stimulation (tDCS; Antal et al., 2017). By delivering weak currents via sponge electrodes that are placed on the scalp, the stimulation is hypothesised to modulate neural excitability by acting on the resting membrane potential (for a review see Nitsche et al., 2008, Nitsche and Paulus, 2011).

Several studies have reported that treatment effects are increasing with prolonged or repeated exposure to transcranial electrical stimulation (tES) (Loo et al., 2012, for a review see Brunoni et al., 2012). So far, however, stimulation sessions largely require on-site supervision that limits the frequency of treatment due to facility and material availability as well as high cost for personnel (Silva-Filho et al., 2022, Maceira-Elvira et al., 2020). Furthermore, the reachability or distance of the facility for patients prohibits a larger outreach, especially as patients may suffer from motor deficits and therefore depend on aided transport or are even unable to reach the facility (Charvet et al., 2015, Bikson et al., 2020). A further challenge to the current mostly on-site stimulation interventions has been introduced by the COVID-19 pandemic, which led to the disruption of many facultative protocols worldwide and calls for the adaptation of these forms of interventions (Bikson et al., 2020, Caulfield and George, 2020).

To offer flexibility and autonomy to patients, home-based, self-applied solutions are being tested as a promising treatment approach (Palm et al., 2018, Maceira-Elvira et al., 2020, Pilloni et al., 2022, Park et al., 2019, Alonzo et al., 2019, Dechantsreiter et al., 2022). In this novel set-up, the stimulation settings and parameters are remotely controlled and supervised to warrant safety of the patient (Van de Winckel et al., 2018, Ahn et al., 2019, Maceira-Elvira et al., 2020, Dechantsreiter et al., 2022). Many studies have, in this context, implemented a pre-set stimulation duration and/or minimum session intervals, as well as automatic stopping functions in case stimulation parameters exceed predefined limits (Cha et al., 2016, Park et al., 2019, Im et al., 2019, Prathum et al., 2021, Ahn et al., 2019, Brietzke et al., 2020, Carvalho et al., 2018).

Chavret and colleagues have formulated a framework of guidelines for clinical trials that use home-based application of tDCS. These include extensive training of the investigator / clinician and patient, dose control, monitoring of compliance and adverse effects as well as an easy-to-use equipment i.e., setting up of electrodes and headgear (Charvet et al., 2015). However, one open challenge in this domain remains: how to ensure the correct stimulation electrode placement by self-application in the home-based setting?

The importance of this matter has been highlighted by studies investigating electric field distributions in both epilepsy patients subject to surgery and modelling (Woods et al., 2015, Opitz et al., 2018). More precisely, it has been strongly recommended to keep the displacement of the electrodes below 10 mm across the stimulation sessions to avoid major changes in electric field distribution (Woods et al., 2015, Opitz et al., 2018), which is especially important when applying high-definition tES that is aiming for more focality (Datta et al., 2009).

Intensive training for cap or headgear placement of either the patients or their caregiver is implemented in most clinical trials using home-based stimulation set-ups (Maceira-Elvira et al., 2020, O'Neill et al., 2015, Ahn et al., 2019, Van de Winckel et al., 2018, Bréchet et al., 2021, Martens et al., 2018). A couple of studies took further measures to aid their participants with references. Cha and colleagues (2016) instructed their participants to place the headband holding the stimulation electrodes centrally, so that "the midline locators were on the vertex and in the middle of the forehead", respectively. The second band was instructed to be placed "just above the eyebrows and over the ears". Van de Winckel and colleagues (2018) defined the correct cap placement on-site and measured the distance between the participants eyebrows and the front edge of the cap holding the electrodes, this then served as an indicator for the patients at home.

Nonetheless, there are no studies so far addressing this issue in a monitored and objective way. For this purpose, we have developed an easy-to-use and cost-efficient tool that uses computer vision and the in-built camera of any laptop or tablet given for training. It guides patients at home, providing them with real-time feedback to place the tES electrodes based on the correct cap placement and tracks the electrode placement for monitoring purposes.

We hypothesise that this technology not only allows for controlled monitoring and guidance of the participant's placement of the cap in each session, but further serves as safeguarding with the potential to induce confidence, as it helps with cap adjustment in real-time. Here, we propose a protocol for testing the general feasibility of the algorithm, an evaluation of its accuracy in comparison to expert-based placement and the user experience and confidence that participants have regarding the cap placement using this novel technology.

2. Methods

2.1. Participants

Thirty-six healthy participants (31 right-handed, 20 females, mean age ± standard deviation (SD): 45.1 ± 20.1, age range: 18–76 years old) were recruited for this study. Fourteen participated in a pilot study evaluating whether there is a difference between two different interfaces (*PROTOTYPE* vs. *CURRENT)* of the algorithm. There were no differences in cap placement accuracy when comparing the two (see Appendix A). However, the qualitative feedback showed that older participants especially appreciated the colours and larger font size of the new interface, whereas younger participants positively commented on the integrated tutorial (both part of *CURRENT*). We therefore decided to use *CURRENT*

for the main study and to integrate our results regarding this version from the pilot study into the main study. Twenty-two participants took part in the main study. Participants for both the pilot and the main study were recruited using the following inclusion criteria: ≥ 18 years of age, above cut-off score (>26/30) on the Mini Mental State Examination (MMSE, Folstein et al., 1975), absence of neuropsychiatric diseases and contraindications for NIBS and Magnetic Resonance Imaging (MRI). All participants gave written informed consent before starting the study. The study was performed in accordance with the declaration of Helsinki (World Medical Association Declaration of Helsinki, 2013), except for registration in a database. The approval was obtained from the cantonal ethics committee Vaud, Switzerland (project number: 2018-00889).

2.2. Face recognition algorithm

The algorithm uses a simple in-built tablet camera that captures a set of QR-like markers that are placed on a neoprene cap holding the stimulation electrodes. During the first on-site visit, individualised cap placement is completed by a NIBS-expert investigator following 10–20 EEG systems guidelines (Homan et al., 1987). An algorithm based on facial recognition saves the cap placement using the QR-like markers together with individual facial key points as a reference for the subsequent sessions. During the verification process at home, the algorithm either confirms correct placement of the cap or helps the patients with visual feedback to adjust the cap with respect to the reference; it also saves the distance on three axes from the reference in a csv file for post-study investigations. For a thorough description of the algorithm, the QR-like markers and a screenshot of the interface please see Appendix B and Appendix C.

2.3. Experimental design

2.3.1. Pilot study

The study followed a randomised cross-over design and was composed of short experimental sessions separated into three days. Evaluating the protocol feasibility and interface of the algorithm, the first 14 participants (7 females, mean age ± SD: 48.4 ± 21.6, age range: 20–76 years old) performed the following sessions: Day 1, they were informed, consented and screened. Next, structural images were acquired (if not available) during a short MRI scan (T1-weighted anatomic images have the following parameters: TR = 2300 ms, TE = 2.96 ms, slices = 192 slices, slice thickness = 1.0 mm, inversion time = 7.1 ms, flip angle = 9°; voxel size = $1 \times 1 \times 1$ mm^3, field of view = 256×256 mm^2). The images were read into a Neuronavigation system (Localite, Bonn, Germany) that served to capture electrode positions (RAS coordinate, see Fig. 1). The participants' cap placement performance was compared with a tES trained investigator's cap placement in the following three conditions: 1. Before the investigator with instructions (*Pre*), 2. after the investigator with instructions (*Post*), 3. with the algorithm in the pre-existing interface (*PROTOTYPE*) and 4. with the algorithm in a newly designed interface including a tutorial (*CURRENT*). The latter was designed to facilitate autonomous usage of the algorithm through step-by-step guidance, which we hypothesised to be beneficial especially for older participants, those with little technological experience, or for patients. It is important to note that the difference between the two algorithms is purely related to the interface, meaning that the face recognition algorithm represents the backbone of both of them. On Day 1, *Pre* was performed, as well as the correct placement by the investigator, and *Post*. *PROTOTYPE* and *CURRENT* were then randomised across participants on Days 2 and 3.

2.3.2. Main study

Following the validation of the new interface (see results of the pilot study in Appendix A), 22 participants (13 females, mean age ± SD: 43.0 ± 19.3, age range: 18–73 years old) were subject to a screening and MRI session, *Pre* and the investigator placement on Day 1, followed by Day 2 and 3 with either *Post* or *CURRENT* in randomised order. A subset of participants (N = 6, 4 females, mean age ± SD: 43.8 ± 23.1, age range: 27–73 years old) were additionally tested one week later using the algorithm (*FU_CURRENT*) and with instructions only (*FU_Post*) to evaluate cap placement accuracy and confidence over a longer time-span with a wash-out period in-between.

Each Neuronavigation recording was performed twice per condition and later-on averaged. The root mean square of co-registration error was aimed to be kept below 3 mm for each participant in each cap placement. An overview of the experimental design is given in Fig. 1.

2.4. Cap placement

The cap (neoprene, different sizes according to head circumference) and tablet (Microsoft Surface Go) used for this study are part of the Starstim-Home system by Neuroelectrics (https://www.neuroelectrics.com/solutions/starstimhome, see Fig. 2). For each cap placement, participants were asked to adjust the correct position either according to oral instructions (i.e., "Please place the cap tightly and deeply and close the chin strap. Try to align the midline electrodes to the centre of your face") using the front camera of the tablet (*Pre* & *Post*) or with the help of the algorithm. For the latter, a reference is created on Day 1 with the placement of the investigator. Using the tablet's front camera, the algorithm recognises a set of markers placed on the cap (see Fig. 2) and facial key-points measured a priori. The algorithm maps the 2D camera input into a 3D coordinate space and gives real-time feedback to the participant while placing the cap.

2.5. Confidence & user experience

For both the *Post* and *CURRENT* conditions during the main study (N = 22), participants were asked to rate their confidence about placing the cap similarly to the investigator on a visual analogue scale (VAS), ranging from 0 (not confident) to 10 (confident). Evaluations of the newly created interface of the algorithm were performed using a standard user experience questionnaire (UX, Laugwitz et al., 2008, https://www.ueq-online.org/, 26 items – see Appendix D). We also asked participants to rate usefulness and ease of use on separate VAS scales and for verbal feedback regarding their general comments on the algorithm.

2.6. Monitoring

While the electrode localisation algorithm gives real time feedback, it detects the frames that are below threshold and therefore seen as correct. For each of these frames, the distance of the current cap placement to the reference is saved on three axes (X, Y, Z). Each row of the resulting file therefore represents a measure of cap placement accuracy.

2.7. Data analyses

All statistical analyses were performed in RStudio (RStudio Team (2022). RStudio: Integrated Development Environment for R. RStudio, PBC, Boston, MA URL https://www.rstudio.com/). Statistical significance was assumed for p-values < 0.05. Data were checked for normality via visual inspection of Q-Q plots (ggplot2 package) and using the Shapiro-Wilk test (rstatix package). To

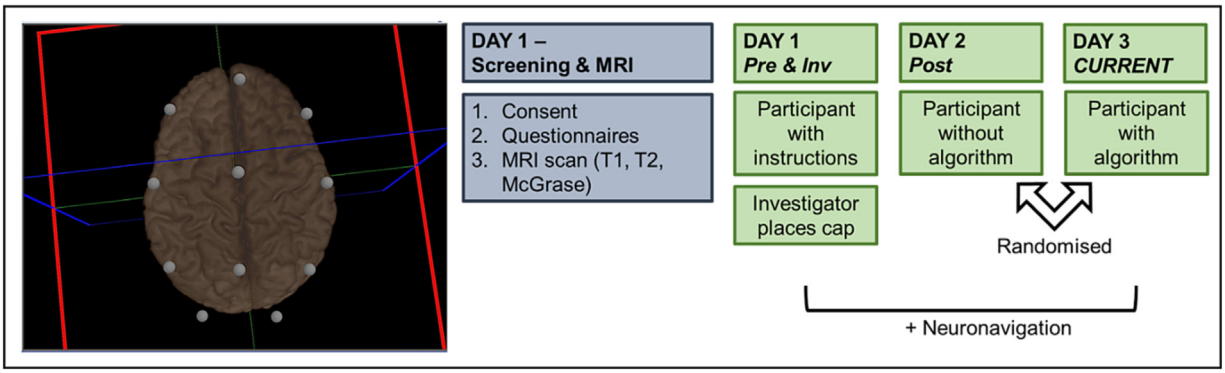


Fig. 1. Experimental design. Main target electrodes F3, Fz, F4 (frontal) and other electrodes recorded for further analyses C3, Cz, C4, P3, Pz, P4, O1, O2 (central, parietal, occipital respectively) used for cap placement accuracy comparison (left); experimental design of the main study (right).

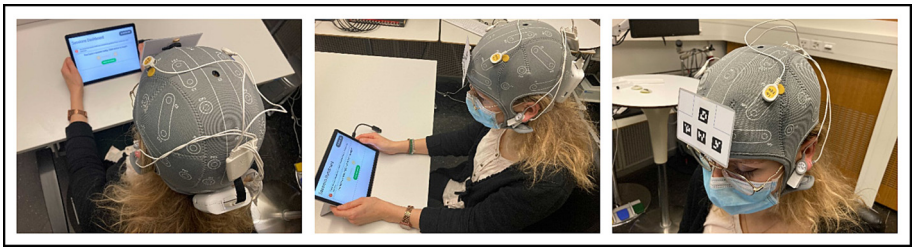


Fig. 2. *CURRENT* complete set-up. Depicted including neoprene cap, tablet and tDCS device (Starstim-Home Neuroelectrics), as well as QR-like markers for cap placement evaluation.

evaluate the accuracy of the algorithm the deviation of each cap placement condition (*Pre*, *Post* & *CURRENT*) from the investigator's placement in 3D space was calculated using Euclidean distance on all three axes: $AB=\sqrt{(x2-x1)^2+(y2-y1)^2+(z2-z1)^2}$ and non-parametric permutation tests for significance to compare not only the mean as a test statistic but also the SD in the different conditions. We first looked at the deviation data of the frontal target electrodes that were the main focus of our study. We then averaged over all eleven electrodes recorded to investigate generalisability of the algorithm. The results of the VAS were compared for the *Post* and *CURRENT* conditions using permutation tests as well.

3. Results

3.1. Cap placements

Data of the pilot- and main-study were combined to compare frontal electrode deviations in the three conditions compared with the NIBS-expert investigator's placement (N = 36). The results are summarised in Fig. 3.

By visual inspection it is evident that most of the cap placements in the *Post* and *CURRENT* conditions range below the suggested maximum 10 mm of displacement (Woods et al., 2015, Opitz et al., 2018) from the investigator's cap placement. Both conditions further reduce the mean deviation compared with the *Pre* condition. For an overview of the individual data points of each participant's frontal electrode deviation please see Fig. 4.

The same trend is seen when averaging over all eleven electrodes recorded. The mean deviation in the *Post* and *CURRENT* conditions is slightly elevated compared with the frontal electrodes, but remains in both conditions below the desired cut-off (see Fig. 5). Variability of the cap placement performance is higher when looking at all electrodes. For an overview of the individual results of each participant's averaged electrode deviation please see Fig. 6.

Following significant Shapiro-Wilk tests for normality of data distribution (all equalled $p > 0.02$), non-parametric permutation tests were implemented to evaluate cap placement accuracy. Permutation tests also allow the comparison of test statistics other than the mean or median. In the case of our results, the variability of data in form of the SD has been used to assess how widely data points are distributed per condition.

Permutation tests were performed with a 100,000-sampling. There was a significant difference between the *Pre* and *CURRENT* conditions when inspecting the frontal target electrodes for the mean ($p = 0.02$) and a trend for the SD ($p = 0.08$). Furthermore, the comparison between the *Pre* and *Post* conditions showed a trend for both measures (mean: $p = 0.07$; SD: $p = 0.05$). No significant differences were found for the comparison between the *Post* and *CURRENT* conditions, nor when examining the comparisons with all eleven electrodes. For a summary of the permutation results, please see Table 1.

To evaluate how the cap placement performance changes over time without further training, a subset of participants (N = 6) performed cap placements another time one week after Day 1 (Follow-Up, FU). As this subset of participants represents a small sample, no statistical analyses were performed. Upon visual inspection of Fig. 7 and Fig. 8, it is evident that apart from one person, all others performed below the desired cut-off of 10 mm during the first 3 experimental days. Notably, the mean deviation is slightly increased during the follow-up session with instructions only (*FU_Post*) but not in the follow-up condition using the support tool (*FU_CURRENT*).

3.2. Confidence & user experience

When comparing the participants' confidence for cap placement on the VAS, we can observe high values for both the *Post*

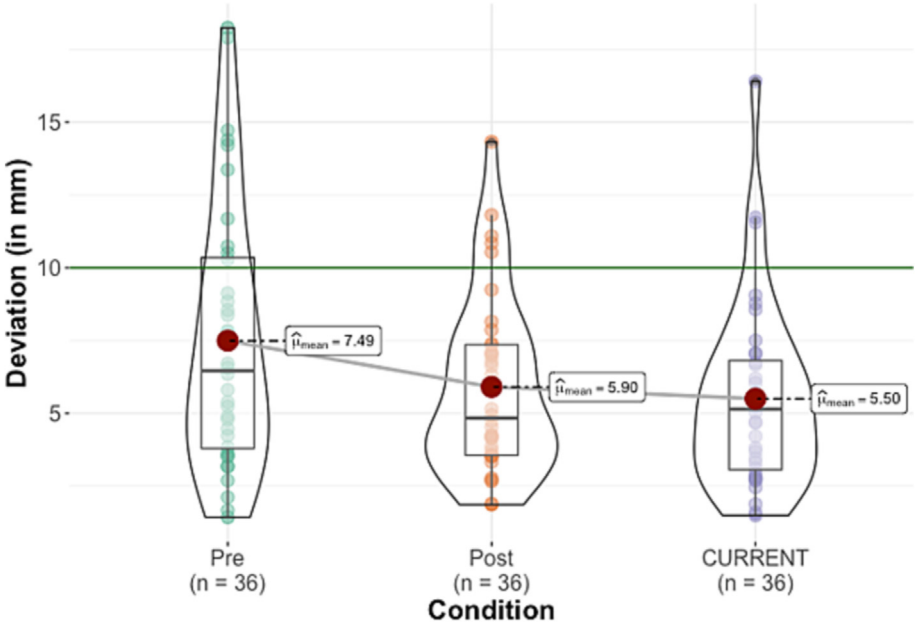


Fig. 3. Deviation (in mm) of the frontal target electrodes (F3, Fz, F4) from the investigator's cap placement in the three conditions (N = 36). The horizontal green line corresponds to the maximum deviation of 10 mm (as suggested by Woods et al., 2015, Opitz et al., 2018).

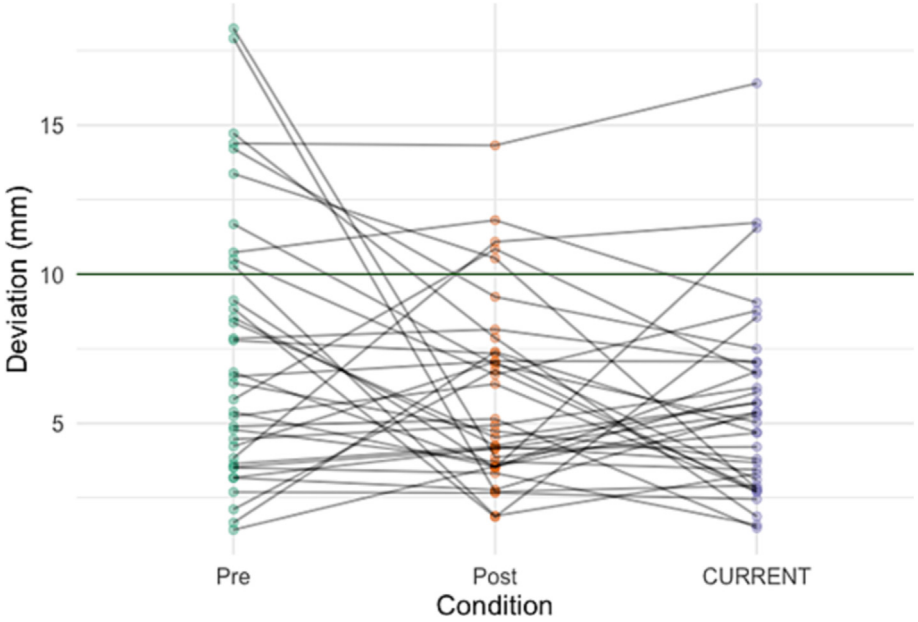


Fig. 4. Individual results of frontal electrode deviations in the three conditions Pre, Post, CURRENT (N = 36). The horizontal green line corresponds to the maximum deviation of 10 mm (as suggested by Woods et al., 2015, Opitz et al., 2018).

and *CURRENT* condition. Upon visual inspection, the range of confidence values seems to be slightly decreased after using the algorithm (*CURRENT*) compared with the *Post* (see Fig. 9). Permutation test did not show a statistical difference between the two for the mean ($p = 0.63$), nor for the SD ($p = 0.8$). It is important to note, however, that participants were generally highly confident about their performance reflecting a satisfactory / desirable outcome for both "after-training conditions", which supports the simplicity of the set-up. In the *Post* condition, the participants rated their confidence on average with 8.07 with an SD of 1.29; whereas in the *CURRENT* condition, confidence averaged on a score of 8.25 with an SD of 1.21. Importantly, confidence ratings increased after the follow-up cap placements (*CURRENT* condition (mean ± SD, 9.33 ± 0.66); *FU_Post* (9.18 ± 0.79)).

The second VAS, performed after the cap placement with the aid of the algorithm, showed that participants rated the easiness to use the algorithm on average 8.02 ± 1.95, and the usefulness of the technology as 7.81 ± 2.53.

The user experience questionnaire used in this study can be summed in 6 major components for which values between −0.8 and 0.8 represent neutral evaluation, whereas values > 0.8 depict a positive evaluation and < −0.8 a negative one. All six points were evaluated as positive, for details please see Table 2.

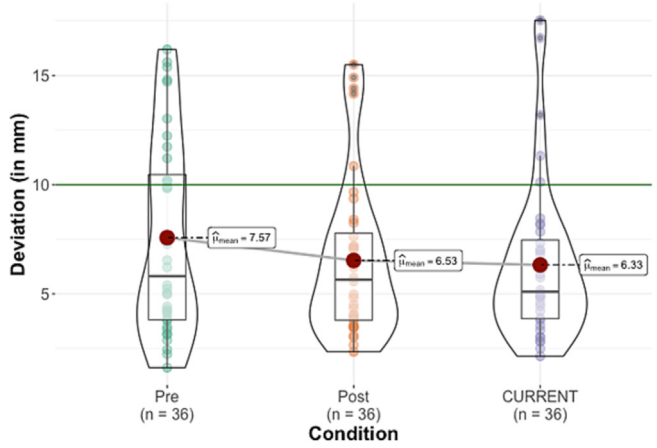


Fig. 5. Deviation (in mm) from the investigator's cap placement, averaged over all electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, O2) in the three conditions (N = 36). The horizontal green line corresponds to the maximum deviation of 10 mm (as suggested by Woods et al., 2015, Opitz et al., 2018).

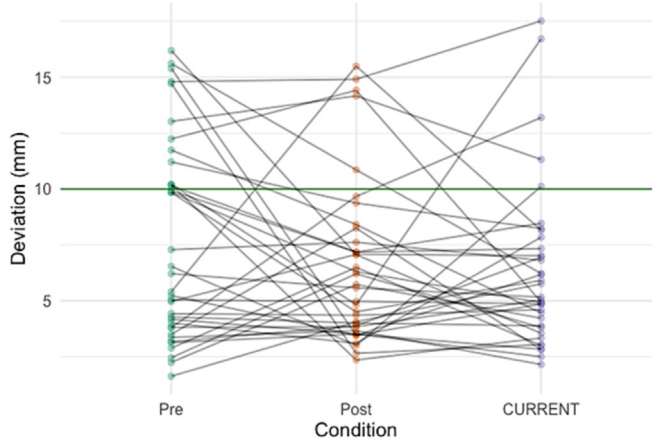


Fig. 6. Individual trajectories averaged over all electrode deviations in the three conditions Pre, Post, CURRENT (N = 36). The horizontal green line corresponds to the maximum deviation of 10 mm (as suggested by Woods et al., 2015, Opitz et al., 2018).

4. Discussion

In the present study, we evaluated performance and usability of a novel technology and framework that guides and monitors patients throughout home-based self-application of tES with a focus on correct electrode placement.

Compared with instructions only and before the investigator's cap placement (*Pre*), the electrode localisation algorithm helps the participants to place the cap significantly more accurate (*CURRENT*). The participants' self-placement supported by the technology was as accurate as the NIBS expert investigators' placement,

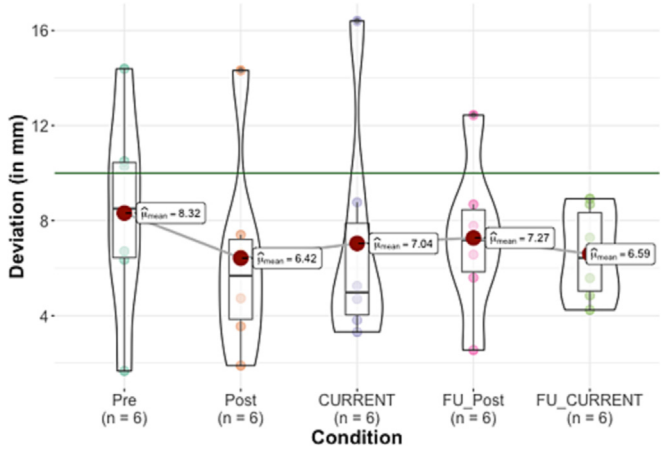


Fig. 7. Deviation (in mm) of the frontal target electrodes (F3, Fz, F4) from the investigator's cap placement in the three initial conditions and one week later (N = 6). The horizontal green line corresponds to the maximum deviation of 10 mm (as suggested by Woods et al., 2015, Opitz et al., 2018).

whereas the *Post* condition only showed a trend towards this direction. There was no significant difference between the *Post* and *CURRENT* conditions, however participants performed satisfactorily in both of them, demonstrating the simplicity and accuracy of the present set-up. The *Post* condition is comparable to the instructions and techniques used in other home-based studies so far (Park et al., 2019), which not only speaks for the importance of training and detailed instructions (Charvet et al., 2015), but also confirms that through the latter, good results can be achieved.

Nonetheless, our results show that *CURRENT* provides distinguishable value to the status quo, as only 3 out of 36 participants placed the frontal electrodes outside the suggested 10 mm deviation range (Woods et al., 2015), ensuring correct cap placements in the majority of cases. This additionally shows that no technical difficulties were experienced by the participants that would lead to a major decrease in performance of cap placement accuracy. It is important to note that participants' deviations were measured with the help of *CURRENT* without any prior training on how to use this technology. This was done to determine how intuitive and easy-to-use the technology is at first usage. We hypothesise that focusing less on the user experience and more on accuracy of CURRENT during the training session might potentially lead to higher accuracy. This, however, will have to be tested in future studies. Importantly, the participants' confidence as well as the cap placement performance did not decrease for the follow-up session 7 days after the initial placements and without further training. This further highlights the simplicity of the set-up as well as the confidence induction through usage of *CURRENT*. Future studies should investigate the evolvement of confidence and accuracy with specific training or after several sessions of using the algorithm.

This novel technology offers, for the first time, the possibility to monitor how well participants perform the cap and electrode placement at home in a session-by-session manner. Through the

Table 1
Permutation test results (100,000 sampling) contrasting the three conditions. Frontal electrodes only are in the left table, all eleven electrodes averaged are in the right table.

Frontal electrodes				**All electrodes**			
Test statistic	**Pre vs. Post**	**Pre vs. CURRENT**	**Post vs. CURRENT**	**Test statistic**	**Pre vs. Post**	**Pre vs. CURRENT**	**Post vs. CURRENT**
Mean	1.59	1.99	0.40	Mean	1.04	1.25	0.20
SD	1.50	1.37	0.13	SD	0.86	0.85	0.02
p-values	**Pre vs. Post**	**Pre vs. CURRENT**	**Post vs. CURRENT**	**p-values**	**Pre vs. Post**	**Pre vs. CURRENT**	**Post vs. CURRENT**
Mean	0.07	0.02	0.65	Mean	0.26	0.18	0.83
SD	0.05	0.08	0.87	SD	0.22	0.23	0.98

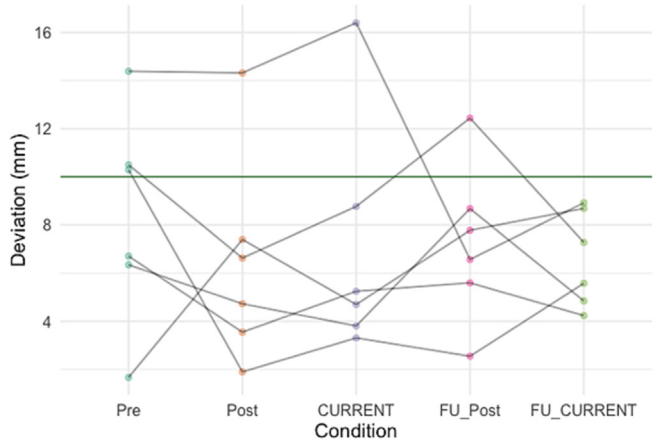


Fig. 8. Individual results of frontal electrode deviations in the conditions Pre, Post, CURRENT, FU_Post and FU_CURRENT (N = 6). The horizontal green line corresponds to the maximum deviation of 10 mm (as suggested by Woods et al., 2015, Opitz et al., 2018).

recording of the cap position on three axes in a simple csv output file, the investigator can monitor whether the cap has been placed similarly to where they placed them during the initial on-site visit following the 10–20 EEG systems guidelines (Homan et al., 1987). Quantifying electrode placement accuracy can represent a useful tool to interpret the results of a home-based study.

Furthermore, we assume that *CURRENT* can be beneficial for different tES techniques in home-based settings. Although tDCS is the most established technique for home-based self-application, transcranial alternating current stimulation (tACS) has been used in this setting in recent studies ((Bréchet et al., 2021, Cha et al., 2021). Novel techniques such as temporal interference stimulation may be implemented in the near future in a similar fashion and profit from the monitoring and confidence inducing aspects that *CURRENT* offers.

We observed high values of confidence of the participants in setting up the tES technology in both the *Post* and *CURRENT* conditions. Contrarily to our expectations, there was no large difference in confidence levels between the two. Encouragingly however, the qualitative feedback we received from participants of different ages indicates an increase in their confidence level and feeling of certainty with respect to placing the cap without the algorithm's help ("The algorithm allows to be 100% sure about a good positioning of the cap. It is easy to use." (63 years old; for more individual feedback please see Appendix E). We hypothesise that this positive

Table 2
User experience questionnaire results split into the 6 dimensions assessed (N = 36). Values above 0.8 indicate positive evaluation.

UX-Q Scales	
Attractiveness	1.16
Perspicuity	1.36
Efficiency	1.19
Dependability	1.00
Stimulation	1.21
Novelty	1.05

evaluation will be particularly important for studies using home-based self-application of tES for a long duration. We anticipate that the beneficial effect of *CURRENT* will increase with prolonged usage and especially with increasing time since the on-site visit / training.

Along these lines, we hypothesise that the use of *CURRENT* might reduce the training time needed to familiarise the patients with the electrode placement at home. Instructions and familiarisation with the material will remain critical for patients and participants to use the set-up safely and the optimal placement by a NIBS-expert investigator that is saved as a reference on the tablet make at least one on-site visit indispensable. However, the qualitative feedback we received indicates a confidence induction by the algorithm which, together with the monitoring function of *CURRENT*, might enable relying on the algorithm earlier and reduce training hours compared with e.g. home-based set-ups in which no monitoring of cap placement is available and training before necessarily intensive (Chavret et al. 2015).

The general feedback regarding the interface and usability of *CURRENT*, assessed via two different VAS scales ("usefulness" and "easy-to-use") as well as a standardised UX questionnaire, yielded positive results, irrespective of technological knowledge. This qualifies the technology to be used by a wide range of participants and patients in the future.

An important point to consider is that there is a bias for accuracy in favour of the frontal electrodes by measuring the cap placement from a frontal perspective. Accordingly, our results show a significant difference in displacement only for the frontal, but not averaging over all eleven electrodes. Using the QR-like markers and a face recognition algorithm to assess cap placements we anticipated this result; however, it will be the challenge of further studies to find comparable solutions for more posterior target regions.

Another limitation of this study is that we did not acquire long-term data from patients at home. However, *CURRENT* is presently

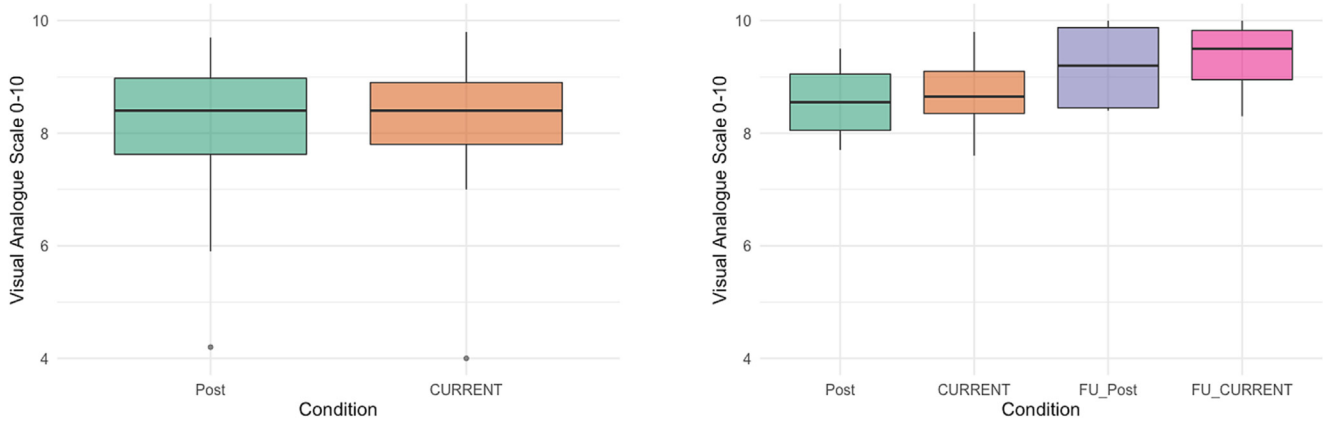


Fig. 9. Confidence rated on a VAS (Visual Analogue Scale) in the conditions *Post* and *CURRENT* (left, N = 22) and for a subset of participants additionally for conditions *FU_Post and FU_CURRENT* (N = 6) performed one week later.

used for a series of sessions in a multi-site, double-blind, randomized and placebo-controlled trial assessing the effects of tDCS combined with a video-game based intervention in major depressive disorder (MDD, https://thediscoverproject.site/, Dechantsreiter et al., 2022). The home-based set-up of this trial consists of a six-week intervention with 114 patients planned to be included with daily trainings. This trial is expected to provide important information about the easiness of use or potential difficulties throughout a longer duration of usage.

In sum, this novel technology based on facial recognition improves the existing set-ups of home-based non-invasive tES in guiding patients during self-application and in monitoring electrode and cap placements. It greatly adds to the growing body of research taking the development of home-based tES set-ups towards creating a controlled environment that can be confidently and safely used by patients. This may increase the possibility of high-frequency treatment strategies that can be integrated easily into the patients' everyday life.

5. Conclusions

- Computer Vision Technology based on a facial recognition algorithm allows to direct and monitor electrode placement for home-based self-application of tES to reduce displacement
- Usage of *CURRENT* favours increased confidence levels of the participants
- Feasibility and user experience questionnaires returned excellent evaluations & feedback regarding the new support tool
- Regarding the open challenges of assisting the patients in a home-based set-up for self-application of tES, *CURRENT* is a significant step forward to guide participants and especially patients towards precise electrode placement and monitoring the accuracy of individual cap placement in a session-by-session manner

Conflict of interest

FP is a member of the European Scientific Advisory Board of Brainsway Inc., Jerusalem, Israel, and the International Scientific Advisory Board of Sooma, Helsinki, Finland. He has received speaker's honoraria from Mag&More GmbH, Brainsway Inc., Jerusalem, Israel, and the neuroCare Group. His lab has received support with equipment from neuroConn GmbH, Ilmenau, Germany, and Mag&More GmbH and Brainsway Inc., Jerusalem, Israel. The other authors report no competing interests.

Funding

This work was supported by ERA-NET NEURON (The DiSCoVer project). The NEURON 'Network of European Funding for Neuroscience Research is established under the organization of the ERA-NET 'European Research Area Networks' of the European Commission. National funding agencies are the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung [BMBF]) for LMU Munich, the Ministry of Health (MOH) for HUJI and Hadassah, the Swiss National Science Foundation (SNSF) for UNIGE and EPFL and the State Education and Development Agency (VIAA) of Latvia for RSU; the Defitech Foundation (Morges, Switzerland) and by the Bertarelli Foundation (Catalyste Program, Gstaad, Switzerland).

CRediT authorship contribution statement

Fabienne Windel: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration. **Rémy Marc M. Gardier:** Methodology, Software, Writing – review & editing. **Gaspard Fourchard:** Methodology, Software, Investigation, Writing – review & editing. **Roser Viñals:** Methodology, Software, Writing – review & editing. **Daphne Bavelier:** Writing – review & editing, Funding acquisition. **Frank Johannes Padberg:** Writing – review & editing, Funding acquisition. **Elmars Rancans:** Writing – review & editing. **Omer Bonne:** Writing – review & editing, Funding acquisition. **Mor Nahum:** Writing – review & editing, Funding acquisition. **Jean-Philippe Thiran:** Conceptualization, Methodology, Software, Resources, Writing – review & editing, Supervision. **Takuya Morishita:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – review & editing, Supervision, Project administration. **Friedhelm Christoph Hummel:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge access to the facilities and expertise of the MRI facility of the Human Neuroscience Platform (HNP) of the Foundation Campus Biotech Geneva supported by the University of Geneva, Geneva University Hospitals and the École Polytechnique Fédérale de Lausanne (EPFL). We further thank Sylvain Harquel for his input regarding the statistical analysis of the data.

Appendix A. Comparison *PROTOTYPE* & *CURRENT*

There were no differences in cap placement accuracy when comparing *PROTOTYPE* with *CURRENT*). For all pairwise comparisons please see Table A1.

Table A1
Pairwise comparisons of the four pilot study conditions (N = 14).

p-value	Pre	Post	PROTOTYPE	CURRENT
Pre	-	-	-	-
Post	0.19	-	-	-
PROTOTYPE	0.50	0.76	-	-
CURRENT	0.32	0.90	0.85	-

Appendix B. Interface of the algorithm during the verification process

See Fig. B1.

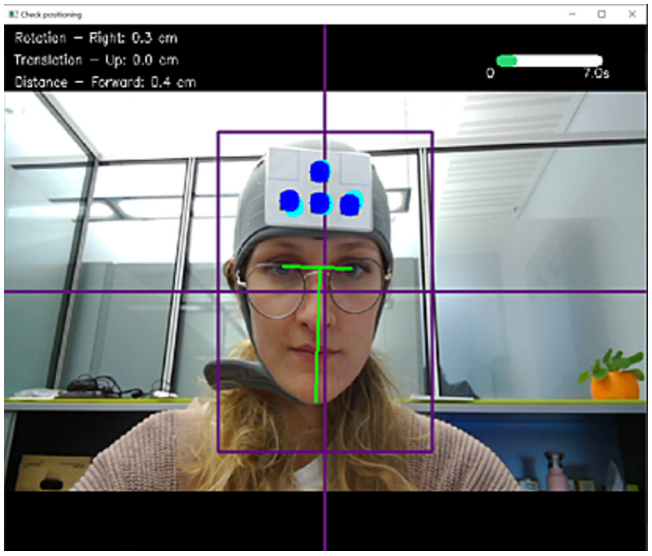


Fig. B1. Screenshot of the CURRENT interface during the verification process. Light blue dots indicate the reference position, whereas dark blue dots indicate the current placement of the cap. The progress bar in the upper right corner fills up as soon as a satisfactory placement is achieved.

Appendix C. Image processing algorithm

The automatic cap placement algorithm is implemented in Python 3.5 using open-source (OpenCV 3, https://opencv.org/) and in-house (LTS5 Face tracker) libraries. The setup consists of a camera filming the patient's face and a cap with QR codes. During the placement procedure, the algorithm receives and processes the images in real time. Because the algorithm is tailored to the patient, calibration is required during the first session on-site. The investigator places the cap on the patient's head, and the algorithm parameters with this particular placement are saved for reference. At home, the algorithm will guide the patient to adjust the cap until reaching the same placement.

The calibration starts with the calculation of the distortion parameters of the camera to ensure proper mapping of 2D pixels to 3D coordinates in the later stages of the algorithm (https://docs.opencv.org/4.x/dc/dbb/tutorial_py_calibration.html). In addition to the camera calibration, the algorithm asks the investigator to measure specific anatomical distances on the patient's head. These are the distances between the eyes, the nose and the chin, the nose and the mouth, and the size of the mouth. Thanks to these measurements and the distortion parameters of the camera, the algorithm estimates the distance of the patient from the camera during the placement procedure. The final step of the calibration is the calculation of the relative position of the cap with respect to the patient's head. This process is divided into three steps: cap detection, face detection and distance calculation.

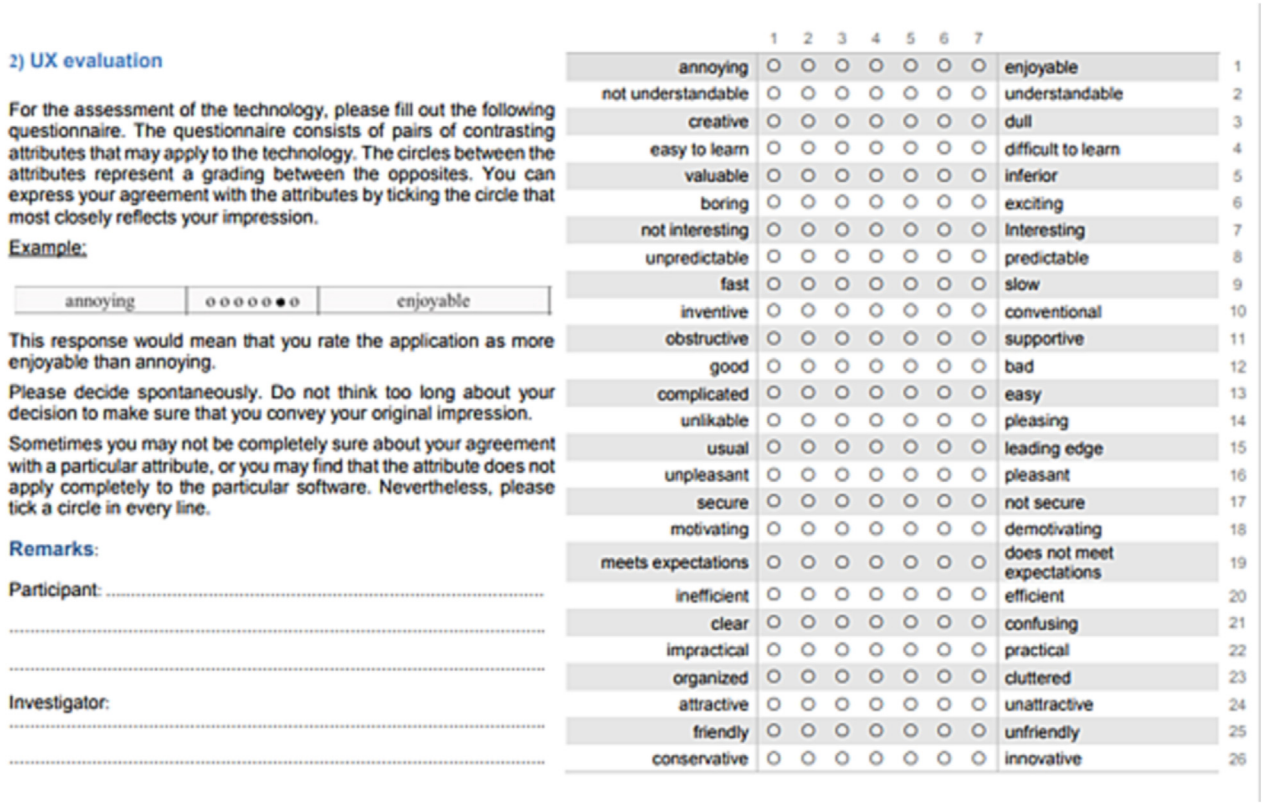
We implemented a cap detection algorithm using ARUCO markers (https://docs.opencv.org/3.4/d9/d6a/group__aruco.html#ga061ee5b694d30fa2258dd4f13dc98129). More specifically, four ARUCO markers with a unique pattern are clipped onto the cap. Because of their unique signature, each ARUCO marker can be detected with its ID, as well as its orientation in space. This makes the algorithm robust to partial detection.

In parallel, the face detection algorithm finds landmarks on the patient's head in the image. The face detector is implemented with the LTS5 face-tracker library (https://lts5facegroup.bitbucket.io/LTS5Doc/index.html). First, the algorithm detects the patient's head using Haar cascade (Viola & Jones, 2001). Secondly, the algorithm calculates the location of landmarks on the detected face using a face alignment algorithm from a training set (Qu et al., 2015). Among these, we keep the ones located around the eyes, the mouth, the nose and the chin because they correspond to the anatomical measurements of the calibration step. From these two detection tasks, the relative location of the cap on the patient's head is calculated by mapping the location of the ARUCO markers and the landmarks from pixels to 3D coordinates (Marchand et al., 2016), and calculating the Euclidean distances between these points. These distances are the references for the placement procedure at home.

Once the calibration is validated by the investigator, the algorithm is ready for the cap placement phase and the patient is able to place the cap autonomously with the guidance provided by the algorithm. During this phase, the cap detection, the face detection and the relative distance calculation are performed for each new image acquired by the camera. The algorithm matches the current relative position to the reference by comparing the distances calculated during calibration. The algorithm gives instructions to the patient until the difference between the new distances and the references is < 7.5 mm that we fixed as the threshold for correct placement.

Appendix D. User experience questionnaire (https://www.ueq-online.org/)

See Fig. D1.



2) UX evaluation

For the assessment of the technology, please fill out the following questionnaire. The questionnaire consists of pairs of contrasting attributes that may apply to the technology. The circles between the attributes represent a grading between the opposites. You can express your agreement with the attributes by ticking the circle that most closely reflects your impression.

Example:

annoying	○ ○ ○ ○ ○ ● ○	enjoyable

This response would mean that you rate the application as more enjoyable than annoying.

Please decide spontaneously. Do not think too long about your decision to make sure that you convey your original impression.

Sometimes you may not be completely sure about your agreement with a particular attribute, or you may find that the attribute does not apply completely to the particular software. Nevertheless, please tick a circle in every line.

Remarks:

Participant: .....

.....

.....

Investigator:

.....

.....

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
creative	○	○	○	○	○	○	○	dull	3
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
valuable	○	○	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
unpredictable	○	○	○	○	○	○	○	predictable	8
fast	○	○	○	○	○	○	○	slow	9
inventive	○	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
good	○	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	○	○	easy	13
unlikable	○	○	○	○	○	○	○	pleasing	14
usual	○	○	○	○	○	○	○	leading edge	15
unpleasant	○	○	○	○	○	○	○	pleasant	16
secure	○	○	○	○	○	○	○	not secure	17
motivating	○	○	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	○	efficient	20
clear	○	○	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	○	○	practical	22
organized	○	○	○	○	○	○	○	cluttered	23
attractive	○	○	○	○	○	○	○	unattractive	24
friendly	○	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	○	innovative	26

Fig. D1. User experience questionnaire evaluating the usability and appropriateness of CURRENT.

Appendix E. Qualitative individual feedback (Participant's quotes)

"The tutorial and the algorithm give me confidence to adjust the position. Particularly the position of my body and head." (73 years old)

"The algorithm and tutorial give confidence & help to place the cap in the right way. The successful trials increase the confidence for future placements at home. It was very easy, explicit and intuitive, more so than using a keyboard. With training, it will be "a piece of cake"." (73 years old)

"I feel surer using the algorithm." (27 years old)

"I oriented myself around the placement of the investigator. This only worked because I still knew it well, later (at home) the algorithm will be necessary." (55 years old)

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