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Teegi: Tangible EEG Interface

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ABSTRACT

We introduce Teegi, a Tangible ElectroEncephaloGraphy (EEG) Interface that enables novice users to get to know more about something as complex as brain signals, in an easy, engaging and informative way. To this end, we have designed a new system based on a unique combination of spatial augmented reality, tangible interaction and real-time neurotechnologies. With Teegi, a user can visualize and analyze his or her own brain activity in real-time, on a tangible character that can be easily manipulated, and with which it is possible to interact. An explorative study has shown that interacting with Teegi seems to be easy, motivating, reliable and informative. Overall, this suggests that Teegi is a promising and relevant training and mediation tool for the general public.

Author Keywords

Tangible Interaction; EEG; Spatial Augmented Reality; Learning

ACM Classification Keywords

H.5.1 Multimedia Information Systems: Artificial, augmented, and virtual realities; H.5.2 User Interfaces: Interaction styles; H.1.2 User/Machine Systems: Human information processing; I.2.6 Learning: Knowledge acquisition

INTRODUCTION

Electroencephalography (EEG) measures the brain activity of participants under the form of electrical currents, through use of a set of electrodes connected to amplifiers and placed on the scalp [17]. This technology is widely used in medicine for diagnostic purposes. It is also increasingly explored in the field of Brain-Computer Interfaces (BCI), the goal of which is to enable a user to send input commands to interactive systems without any physical motor activities, by using brain activity alone [35]. BCI is an emerging research area in Human-Computer Interaction (HCI) that offers new opportunities for interaction, beyond standard input devices [28]. These emerging technologies are becoming increasingly more popular. It feeds into fears and dreams in the general public

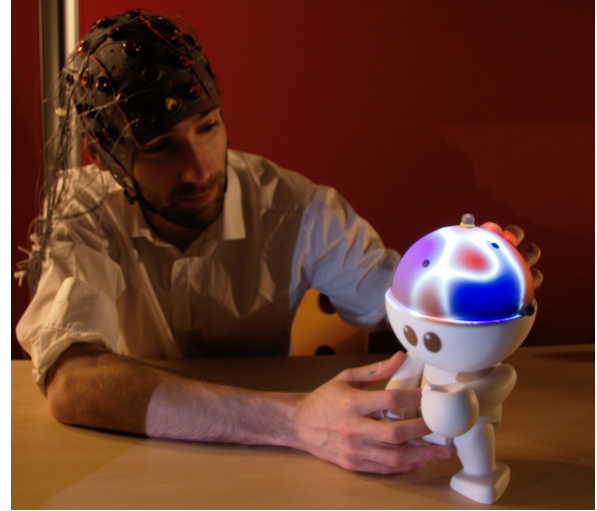


Figure 1. Teegi (Tangible EEG Interface) is a friendly interactive character that users can manipulate to observe and analyze their own brain activity in real-time.

where many fantasies are linked to a misunderstanding of the strengths and weaknesses of such new technologies. *No, it is not possible to read thoughts!* But what can be done exactly? Our motivation is to provide a tool that allows one to better learn how EEG works, and to better understand the kinds of brain activity that can be detected in EEG signals. Beyond the knowledge of the brain that a user can acquire, we believe that a dedicated tool may help demystify BCI, and consequently, it may favor the development of such a promising field.

We followed a multidisciplinary approach, combining Human-Computer Interaction (Spatial Augmented Reality, Tangible User Interfaces), Neurotechnologies (EEG, brain signal processing) and Psychology/Human sciences (Human Learning and Representations, Scientific Mediation) to design an interactive multimedia system that enables novice users to get to know more about something as complex as EEG signals and the brain, in an easy, engaging and informative way. Our final goal is to enhance learning efficiency and knowledge acquisition by letting users actively and individually manipulate and investigate the concept to be learned [31], i.e. EEG signals.

This gave birth to Teegi (Tangible EEG Interface), a physical character that users can manipulate in a natural way to observe and analyze their own brain activity projected in real-time on the character's head (see Figure 1). Beyond the technical description of Teegi, this paper depicts an explorative

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study we conducted, which provides an experimental basis for discussions and future works. Our major contribution for this paper is the design of the first system to make EEG signals and brain activity easily accessible, interactive and understandable. This work is based on theoretical foundations, technical developments, and preliminary investigations.

NEUROIMAGING AND EEG

EEG signals are small electrical currents (in the μV range) that can be measured on the surface of the scalp [17]. They reflect the synchronous activity of millions of neurons from the brain cortex (i.e., the outer layer of the brain). Compared to alternative neuroimaging techniques, such as MagnetoEncephaloGraphy or functional Magnetic Resonance Imaging, EEG is simultaneously cheap, portable and provides good time resolution. Because of these advantages, EEG has been used for many years in medicine, e.g., for the diagnosis of sleep disorders or epilepsy [17]. More recently, with the advance of computer processing performance, it became possible to measure and analyze in real-time the content of these EEG signals. This paved the way for the rise of BCI which uses real-time analysis and decoding of EEG signals in order to identify the mental state of the user and translate it into a command for an application [35].

The currently available tools used to visualize and analyze such signals are tailored for experts with a deep understanding of the brain, EEG principles and EEG signal processing [17]. Figure 2 (left and center) shows some typical visualizations of EEG signals used by experts, i.e., EEG signal traces and a 2D topographic map. More complex visualizations have been proposed, such as 3D topographic maps (Figure 2, right), but they require many mouse inputs to be observed from all angles, which make them inconvenient to use in practice.

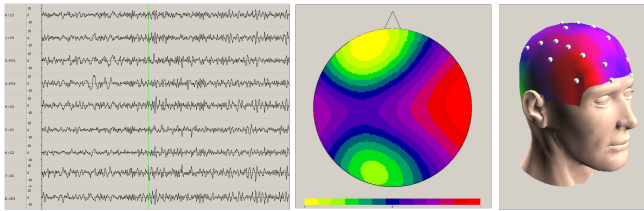


Figure 2. (Left) A trace of EEG signals collected from multiple sensors. 2D (center) and 3D (right) topographic maps. (Screenshots from OpenViBE [23]). The first two views are traditionally used by experts.

Although EEG visualizations are intended for experts only, the general public is often compelled by how the brain works and how its activity is measured. Anyone wondering about brain injuries, epilepsy, sleep or learning disorders, aging, etc. may want to seek further knowledge about how the brain works. Currently, the public is increasingly exposed to neurotechnologies due to the availability of consumer grade EEG devices, such as the Emotiv EPOC or the Neurosky MindWave. Consequently, it has become necessary to design tools and user interfaces which will allow the general public to visualize, understand and interact with EEG signals. For instance, Mullen *et al.* proposed a software solution to process

EEG signals collected using wearable EEG devices and visualize them in 3D [16]. This software enables the user to estimate brain activity sources and connectivity but is still mainly designed for brain signal and neuroscience experts, and not so public-friendly. Another recent work, more suited to lay persons, is the “Portable Brain Scanner” [26]. This system makes use of a consumer-grade EEG device (the Emotiv EPOC) and a smartphone to provide a cheap and portable solution enabling anyone to visualize the sources of their brain activity on their smartphone in 3D. Another more attractive work, which is the most closely related to our Teegi system, is the “Mind-Mirror” system [15]. This system combines Augmented Reality (AR), 3D Visualization, and EEG to enable users to visualize their own brain activity in real-time superimposed to their own head, thanks to a semi-transparent mirror-based AR setup.

This short review of the existing literature about making EEG accessible to the general public revealed that this is still a vastly unexplored area. Moreover, these solutions do not take into account any representation that the general public may have regarding the brain and EEG signals – many lay people do not even know what EEG signals are – in order to provide suitable visualizations and interaction devices to better understand these concepts. Some rare studies have indicated that misconceptions about brain functions prevail in general public [7, 10, 25]. These works stress the importance of popular scientific communication and indicate that communication efforts should be focused on increasing public awareness. It is important to note that the existing works mentioned above are mostly centered on visualization, with little or no interaction possibilities to manipulate and understand the EEG signals in real-time and in a friendly way. This further deters the general public from understanding brain activity [30]. Therefore, with the aim to enhance general public awareness, our work associates technical innovation and user-centered design.

INTRODUCING TEEGI

Founding principles

Design choices were made according to pedagogical principles. It has long been recognized that learner-centered education is much more effective than transmission-based education, even in informal situations [33]. According to the constructivist paradigm, people create unique personal meanings by reflecting on interactive learning experiences. Therefore, people/learners should investigate and manipulate in order to become conscious of complex phenomena, change their misconceptions and construct scientific knowledge [31]. In association, meaningful models play an important role in this type of learning processes [9]. This motivated the design of an anthropomorphic interface that can be freely manipulated.

Our user-centered interactive media uses Spatial Augmented Reality (SAR) and tangible interaction. SAR, introduced by Raskar *et al.* [22], adds dynamic graphics to real-world surfaces by the means of projected light. Many systems were designed using projectors to add “painted” surface [22] or to give the illusion of virtual elements actually being there [34, 2]. A related approach is Tangible User Interface (TUI). TUI

is concerned with providing tangible (i.e. physical) representations to digital information and controls [24]. One of the strengths of tangibles is their situatedness: the interaction takes place in a real-world environment that often hides most of the technological aspects to expose physical interaction components only. They are particularly well suited for mediation purposes as they tend to be more inviting compared to mouse-screen based interfaces [12].

SAR and TUIs are often found together [29, 21]. They are very complementary in that they both take place in the real world, in a common canvas. The tangible interaction allows for a hands-on approach by offering different input affordances (as well as physical constraints) to the user while the SAR technology allows for a flexible and situated way to give feedback. SAR can also be used as an affordable way to embed dynamic graphics on a physical surface that would otherwise require curved displays [4] or rear projection [3].

There are examples of systems that use either tangible or AR principles to interact or review physiological data. Hinckley *et al.* [11] designed a system which used tangible props to do neurosurgical planning. A small tangible head was used in conjunction with a plastic plane to select the cutting planes to be visualized on a screen. Also mentioned above, the “Mind-Mirror” [15] is the work closest to Teegi. However, with Teegi, the data is not co-localized with the data source. It provides flexibility and easier visualization as the users can change viewpoints by tangible interactions instead of rotating their head while keeping their eyes on the mirror. This “out-of-body” visualization also enables collaboration where multiple users can explore the data.

General description

Teegi is a tangible interface that enables users to visualize and analyze a representation of their own brain activity recorded via an EEG system in real-time and displayed on a physical character. After some processing of the raw signals, a dedicated visualization is projected directly on top of the character. This character is tracked, which allows us to co-locate the projection with the character’s head, at any time. Hence, the user can easily visualize a realistic modeling of the EEG signals in any part of the scalp by manipulating the character, while maintaining a good spatial topology of the observed data. Teegi was purposely given a child-like appearance, as well as animated eyes (also projected) that blink at the same time as the users do, in order to breathe life to the character and enhance attractiveness. Indeed blinking can be easily detected in electrodes neighboring the eyes.

Three different filters can be applied to the raw data (see the technical section for details) enabling users to investigate influences of motor motions, visual activities or meditation, on their brain activity in real-time. To remain consistent with the tangible philosophy of this project, we decided to control the filters by way of small tangible characters (mini-Teegis) that can be moved on a “filter area”, which is highlighted on the table by a projected halo (see Figure 3). For example, if a user wants to apply a filter that will allow her to better see what happens when moving her hand, she just needs to take the dedicated mini-Teegi, i.e. the one with the colored hands,

and to move it to the filter area. Then, by moving her right hand, she should see changes in EEG amplitude on the left hemisphere of Teegi’s head, as illustrated in Figure 4. The manipulation of Teegi requires a motor activity. Therefore, when the motor filter is on, manipulating Teegi will obviously lead to observable changes in brain activity.

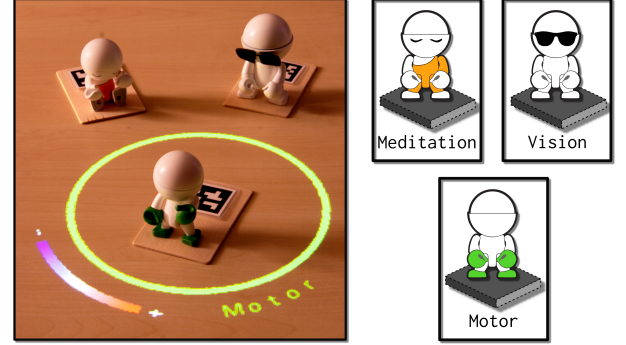


Figure 3. Three mini-Teegis can be used to apply high-level EEG filters to highlight brain processes associated to *Motor*, *Vision* and *Meditation* activities. To do so, the user simply needs to move the desired mini-Teegi into a specific zone projected on the table (green circle).

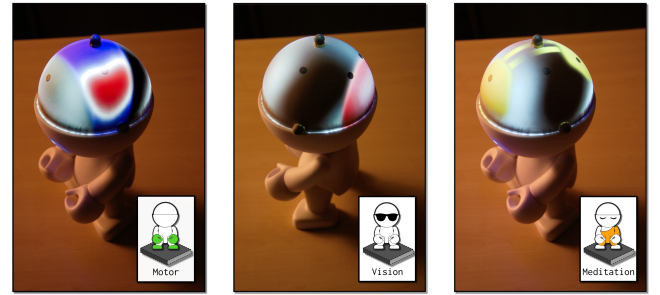


Figure 4. Examples of the displayed visualizations on Teegi for each of the provided filters. Once a filter is active, the brain area corresponding to the selected and processed activity is highlighted in colors while the remaining EEG signals are displayed in grayscale.

At the end of this paper, we present an explorative study we conducted to obtain feedback about the main features of Teegi. However, Teegi is not limited to these first features. In the next section, we describe additional interaction metaphors we have explored, and that may benefit more advanced users. These advanced features were not evaluated during the study.

Advanced features

Visualizing the raw signal recorded on each electrode of the EEG is not very informative for the general public. However, this can be instructive for students who are learning EEG signal processing and analysis. In our approach, we can display on the table these raw data, as shown in Figure 5 (left). This creates a visual link between what is recorded with the EEG system, and the visualization that is provided on Teegi’s head. This is possible because we know the rough position of the user, and the exact position of Teegi. When applying a filter, as described in the previous section, the user can see the effect

of his or her action on the signal (see Figure 5, right). Compared to a standard approach where everything takes place on a screen, we believe that such a spatial and tangible approach might ease the understanding of the filters' effect.

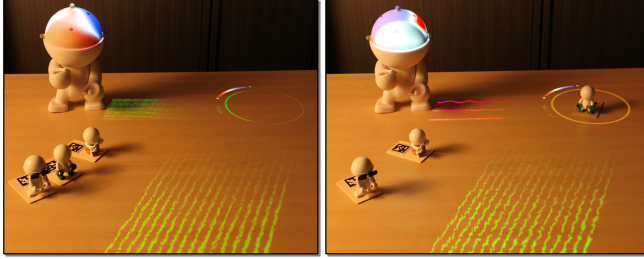


Figure 5. (Left) The raw EEG readings are displayed going from the user to the filter area and then rerouted towards Teegi. (Right) When a mini-Teegi (*i.e.* a filter) is active, the corresponding filtered signals are displayed between the filter area and Teegi instead.

Another dimension we explored is the use of tangible actions to control some parameters of the EEG signal processing. As an example, we have implemented a technique where the user can control the amplitude of the visualization color map by moving a tangible object on the table (figure 6). This could be useful to reveal tiny fluctuations of EEG signals. With such interaction techniques, the whole analysis could be conducted without the use of a screen or a mouse, which remains consistent with the tangible philosophy of the project.

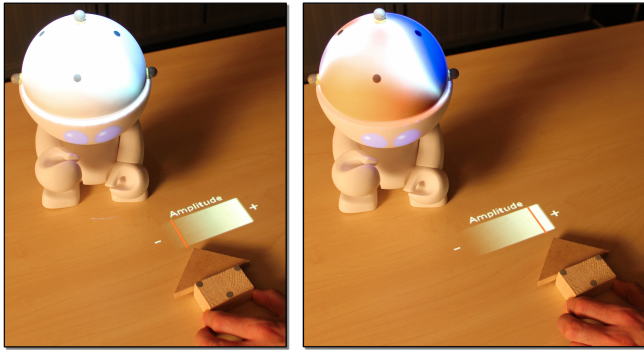


Figure 6. A moving tangible cursor is controlling the amplitude of the visualization color map.

Finally, we developed a solution that highlights the relationship between EEG signals and localized cortical sources, that is where the signals come from *inside* the brain. Using sLORETA inverse modeling [19] and Brainstorm to compute the kernel matrix [27], we obtained a model of the cortex containing 2002 voxels linked to the 32 EEG electrodes we used. We can then project in real time the activity which arises from the outer regions of the cortex on an object representing the brain, alongside with Teegi (Figure 7). Since both Teegi and the brain proxy are tracked, it becomes possible to manipulate two synchronized representations of the same brain activity (the source at the surface of the brain and the measures on the

scalp). This opens way to mediation activities that are more advanced all the while keeping the simplicity and ease of use brought forth by using SAR and tangible interaction.

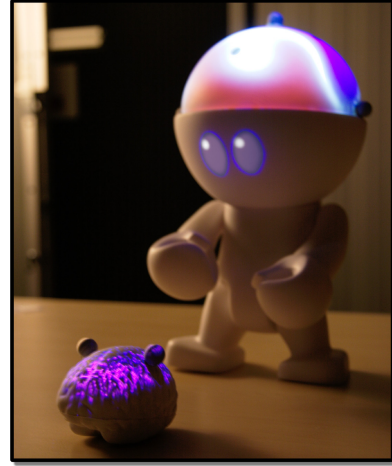


Figure 7. Using an inverse model, the cortical activity and EEG measures are presented together to users.

TECHNICAL DESCRIPTION

EEG

We designed different EEG signal processing pipelines that each create a specific visualization tailored to identify specific elements in the signal. The details of these pipelines are transparent to the user. Each pipeline corresponds to a mini-Teegi filter. In particular, we set up the following EEG signal processing pipelines:

1. Wide-band EEG activity: EEG signals were band-pass filtered between 3 Hz and 26 Hz, in order to filter DC drift and part of the artifacts (e.g., facial muscle activity [8]) that may pollute them. Their power is then computed before being displayed. This corresponds to unspecific brain signals, hence they were labeled as "raw" signals.
2. Sensorimotor activity: EEG signals were first band-pass filtered in the β band (16-24Hz), a brain rhythm highly involved in sensorimotor tasks [20]. Then, they were spatially filtered, *i.e.*, the signals from several neighboring EEG sensors were combined in order to enhance the signal of interest. In particular, we used and displayed Laplacian spatial filters around electrodes C3, C4 and Cz. This enabled the users to visualize EEG activity changes due to movements of the left hand, right hand and feet. Indeed, it is known that the power of EEG signals in the β rhythm decreases in electrodes C3/Cz/C4 during right hand/feet/left hand movements respectively, and increases just after the end of this movement [20].
3. Visual activity: EEG signals were band-pass filtered in the α band (8-12 Hz), then only electrodes P3, Pz, P4, PO3, PO4, O1, Oz and O2 (located on the back of the head, above the neck) were selected and displayed. These electrodes are indeed located over the visual cortex of the brain, *i.e.*, the brain area in charge of visual information processing. The amplitude of the α rhythm is actually known to increase while the user is closing his/her eyes and is thus

not processing any visual information [17]. To ensure that the user could perceive this increase after he/she reopened his/her eyes, the visualization was delayed by 0.5s.

4. Meditation: on a more exploratory note, we used the synchronization between the signals from the anterior and posterior cortex (AFz/Pz), which was measured in a 7-28 Hz band with instantaneous phase locking value [13]. There are different outcomes (increase/decrease in synchronization) depending on meditation type. Mindfulness and body focus practices decrease the synchronization while transcendental practice increases it [14].

EEG signals were acquired with a 32-channels EEG device (made of two g.tec g.USBamp EEG amplifiers). This professional-grade system ensured that our prototype had a good signal-to-noise ratio and accurate electrode location, avoiding unneeded uncertainties. Signals were processed in real-time using OpenViBE [23]. For pipelines 1 to 3, the displayed colors correspond to signal power strength; for pipeline 4 they correspond to the degree of synchronization.

Spatial Augmented Reality

In order to create an augmented character, we have designed a tabletop augmentation setup (see Figure 8). Teegi itself is a 25cm high Trexi DIY toy. The mini-Teegis are also 10cm high Trexis. The main program handling the whole installation was created with vvvv [1]. The primary projected content (Teegi augmentation and GUI display) is handled with a single wide lens projector ProjectionDesign F20SX of resolution 1024x768 located over the table in a top-down orientation. The tracking of Teegi is achieved with an OptiTrack V120:Trio. It runs at 120 FPS with an overall latency of 8.3ms and a precision of 0.8mm. The OptiTrack is located in the same configuration as the main projector and both devices are calibrated together manually. The tracking data is sent to vvvv using OptiTrack's NatNet protocol. Teegi's eyes are projected using a second projector (Vivitek Qumi Q2) that is located on the side of the table.

The filter selection is done using a Sony PSEye web camera pointed at the position of the program selection GUI. Each mini-teegi representing a filter has a fiducial marker attached to it. The library ARToolkitPlus [32] is used to detect which marker is currently selected.

The EEG signals are processed by the OpenViBE software [23] that also generates a grayscale texture of the scalp signals. This texture is then exported to a local shared samba folder which is then fetched and remapped to an appropriate color scale in vvvv before being mapped to Teegi's head. In addition, the raw EEG signals are sent to vvvv over VRPN for display purposes (see Figure 5).

EXPLORATIVE STUDY AND DISCUSSIONS

Protocol

We conducted an explorative study where participants had to manipulate Teegi following a given scenario. The objectives of this study were to i) evaluate the general usability of the interface and ii) obtain initial feedback about the relevance of the approach to help users understand EEG signals and the

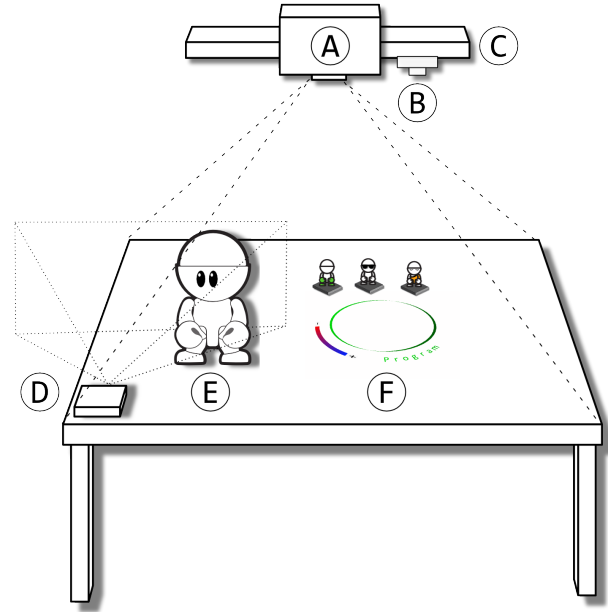


Figure 8. Diagram of the installation. (A) ProjectionDesign F20SX projector (B) Sony PSEye web camera (C) OptiTrack V120:Trio (D) Vivitek Qumi Q2 projector (E) Teegi (F) Program selection zone and mini-Teegis.

brain. Ten participants (6 males, 4 females, mean age 28.6 (SD=9.7)) took part in this study. Pre-tests confirmed they were rather naive on the subject. They manipulated the version of Teegi described in the General Description section (no advanced features). The general procedure was as follows:

1. Pre-tests: The participant answered a first questionnaire assessing his or her representation of the brain. The participant then filled in different forms to measure his or her previous knowledge; one form per studied brain process (motor, vision and meditation).
2. Setting-up: The experimenter positioned the EEG cap on the participant's head. In parallel, the participant, guided by the experimenter, was made aware of the four didactic "cards" explaining the different filters *i.e.*, *Motor*, *Vision*, *Meditation* and *Raw*. Each card was comprised of an image of the mini-Teegi associated with the filter along with basic instructions to follow (e.g. the *Motor* card indicated to the participants to move their hands or feet while staying relaxed). There were also two cards describing the two types of visualization participants could face, *signal strength* and *synchronization*. Once the participant was equipped, a quick calibration phase occurred. While Teegi was still inactive, participants were asked to close their eyes for a few seconds, and to move their hands and feet in order to identify the baseline activity for visualization.
3. Personal Investigation: The participant was asked to freely manipulate Teegi as well as the filters to be able to answer the following questions:
 - What happens when you move your hands or feet?
 - What happens when you close your eyes?
 - What happens when you meditate?

During the whole study the participant sat comfortably in a chair. To avoid the occurrence of muscle artifacts that may pollute the signals, the user was instructed to stay relaxed and to refrain from making strong head movements.

4. Post-tests: The participant answered the questions above on dedicated forms, the same that were given at the beginning of step 1. Finally, he or she filled in a user survey questionnaire based on a 7-point Likert scale.

The whole session lasted approximately 1.5 hours per participant, with 15 to 20 minutes of hands-on time with Teegi. Each session was video-recorded. Video segments were separately visualized and labeled with the corresponding behavior (i.e. tangible and visual interactions, emotional expressions, and investigation strategies) using The Observer XT® 11.5 (Noldus, Info Tech, Wageningen, The Netherlands). After the session, the experimenter had an informal talk with the participant. He corrected the answers, making sure the participant was not leaving with false knowledge, and explained in more detail some aspects of the system (e.g. relationship between visual filter and attentional states, the various effects of meditation, ...). This phase lasted from 30 min to 1 hour depending on the participant's curiosity.

Results and discussions

To better understand the inherent strengths of Teegi towards learning, we assessed three main aspects of Teegi: its technical reliability, its relevance to ease understanding for non-experts, and the User eXperience (UX) it provides. This evaluation is based on 1) the results of the questionnaire that are summarized in Figure 9, 2) the analysis of the video recordings, and 3) the analysis of the forms the participants filled in to assess their pre and post-knowledge of the brain and EEG.

Technical reliability

Participants unanimously reported that the whole system worked properly. The quality of the SAR display is valued by the participants. In particular, they reported that the resolution was appropriate, and they did not report problems of offset between the display and the physical character. Participants declared that they were not disturbed by occlusion problems. The mild temporal delay between their action and their consequences seems not to be an issue.

Manipulations of Teegi were numerous and frequent. Teegi was touched or moved on average 25% of the session's duration, twice per minute. These manipulations consisted mostly of rotations, and to a lesser extent of lifting Teegi to enhance visual perception. Two participants reported difficulties in grasping Teegi while the remaining 8 were comfortable with the form of the character. Video analyses did not show difficulties for the manipulation of Teegi. Similarly, applying filters by manipulating the mini-Teegis seemed easy for the participants.

Relevance of the interface to ease understanding

The participants reported that they understood the visualization associated with the filters. Video analyses indicated that they systematically used all filters several times (3 times per session on average) for a similar duration (Raw filter : 30.4%

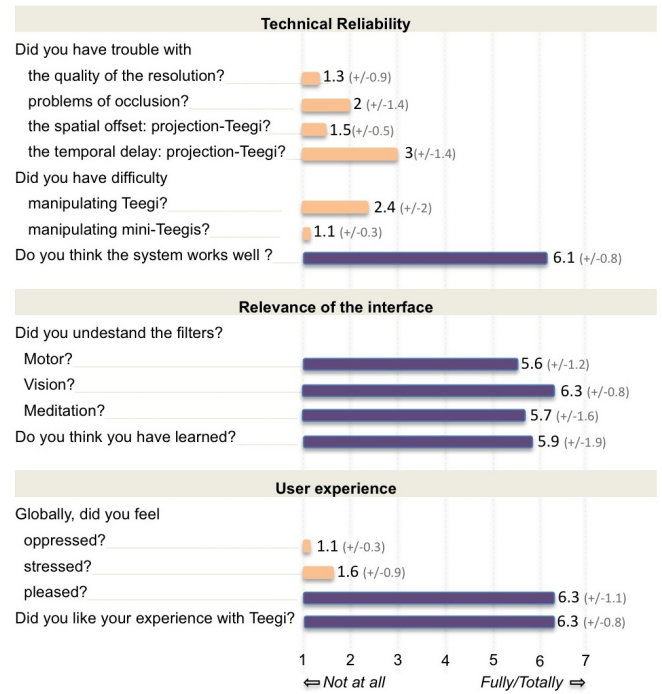


Figure 9. Results of the questionnaire (selected questions). Note that purple (resp. orange) bars indicate questions measuring Teegi's qualities (resp. limitations).

(SD 13.3) of session duration; Motor filter: 26.0% (8.3); visual filter: 16.9% (5.5); meditation filter: 26.6% (8.7)). Interestingly, the visual activity filter seemed slightly easier to understand than the other filters. Moreover, video analyses indicated that the participants did not have difficulty observing the signals on Teegi's head, as soon as they found the right location to observe. Overall, participants reported that they were able to use Teegi without any difficulties.

All participants completed the required tasks. They used instruction cards 5 times per session on average. They reported that they could focus on the tasks rather than on the mechanisms used to achieve them. This suggests that Teegi is a rather transparent interface. Regarding learning of brain processes and EEG, participants reported that they believed they had learned while doing the study. This was confirmed by the results of the pre- and post-test assessments (see Figure 10). These assessments focused on the recognition and the understanding of brain activation during Motor activities, Visual activities and Meditation. Understanding was marked as acquired if 1) the activated areas were correctly localized and 2) the explanations of the brain process were correct. It was marked as under way if only 1) or 2) was satisfied but not both; and as not acquired if neither 1) nor 2) were satisfied. The marks obtained by the participants improved after using Teegi. Overall, this suggests that Teegi offers many interesting features to ease learning and mediation.

All our results indicate that Teegi clearly promotes real-time tangible interactions, which contributes to enhancing awareness. Constructivism and inquiry-based science education principles indicate that, to become conscious of complex phe-

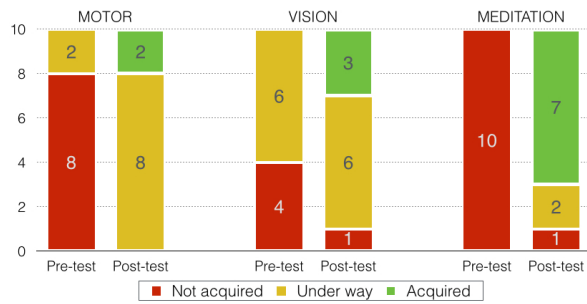


Figure 10. Marks obtained by the participants during the pre- and post-test assessments. See text for details.

nomena and construct scientific knowledge, people/learners have to experiment by interacting with and physically manipulating the content [30]. This is particularly true for brain activity that is difficult to understand because it cannot be sensed [6], contrary to other activities (e.g. respiratory) that are perceived through sensory-motor mechanisms. Hence, brain activities need to be conceptualized, and the success of learning processes strongly depends on the interface. Teegi, which has been largely promoted by the participants, seems to fulfill this function.

User eXperience

The general experience with Teegi was rated as pleasant, attractive and stimulating, and participants did not feel stressed or oppressed. Overall, participants reported that they liked interacting with Teegi. The emotion expression analyses confirmed those statements. They showed that on average participants expressed curiosity and questioning about Teegi feedback during almost 20% (20.1% SD=9.1) of the manipulation duration. Other emotion expressions observed for all participants were joy and pleasure (e.g. smile, laugh, joyful verbal expression...). They occurred during almost 10% (9.8% SD=6.7) of the interaction duration with Teegi. Surprise emotions were observed but less frequently. Interestingly, boredom, weariness expressions occurred rarely (only for 2 users) and only at the end of the manipulation time. We did not observe any occurrence of exasperation or irritation. These results suggest a high level of acceptance for Teegi. This is a fundamental requirement for a tool aiming at improving access to knowledge.

Behavior observations indicated that the majority of participants spoke with Teegi and used morphological zones specific to human interactions while manipulating it. For example, they held its hands and held it up by the waist as one would do with a child. Some users spoke in the first person when they observed changes on the character's scalp for example "so, when I move my hands, I light up on the sides"; many said aloud that Teegi was their own image, for example "so, Teegi is me!". This identification suggests that an activation of associations between the perceived character's personality and self-perception may have occurred [18]. It is known that identification can be associated with increasing loss of self-awareness, and its temporary replacement with elements of the perceived character's personality [5]. Therefore a human shaped, child-like character, made lifelike by animated

projected eyes, could enhance both empathy and implicit self-perception of one's own brain activity, as provided by our interactive media. The anthropomorphic appearance of Teegi could explain the motivation and positive UX reported by the users. All these hypotheses would be the aim of a more extensive UX study.

Regarding visual attention, the participants were apparently paying attention to Teegi most of the time (83.3%, SD 7.6). This supports the fact that Teegi mobilized user attention. It also indicates a cognitive user engagement. Personal investigations were permanent (only 1.9% of inactivity was measured during the session duration; SD=1.7). Behavior analyses indicate that participants made predictions, hypotheses and tested them by conducting experiments. Numerous trial and error strategies were frequently used. This clearly indicates personal active control of the task and inquiry processes. Overall, Teegi stimulates investigations and encourages persistence in task completion.

CONCLUSIONS

In this paper, we presented Teegi, a tangible interface that makes EEG understandable to non-expert users. Our main contribution is the interface itself, which is built from both theoretical foundations, notably from human learning and scientific mediation and technical developments, including spatial augmented reality, tangible interaction and real-time neurotechnologies. We also demonstrated that this interface was well accepted by a first pool of users. In the future, we plan to make a more in-depth investigation into how well users are able to learn about EEG and brain activity with Teegi. To this end, we will conduct dedicated experiments with students and/or visitors in scientific museums. We would also like to precisely evaluate how Teegi benefits learning compared to standard approaches. For more advanced users, ad-hoc tangible filter creation could prove to be of great interest, adding flexibility to the overall system. Finally, it is known that BCI requires the user to learn to control his/her own brain activity to input computer commands [35], which is a long and tedious task. We expect Teegi to be a motivating and informative way to support this training in the future.

REFERENCES

1. vvvv. <http://vvvv.org>.
2. Benko, H., Jota, R., and Wilson, A. Miragetable: freehand interaction on a projected augmented reality tabletop. In *CHI '12*, ACM (2012), 199–208.
3. Benko, H., Wilson, A. D., and Balakrishnan, R. Sphere: multi-touch interactions on a spherical display. In *UIST '08*, ACM (2008), 77–86.
4. Brockmeyer, E., Poupyrev, I., and Hudson, S. PAPILLON: Designing Curved Display Surfaces with Printed Optics. In *UIST '13*, ACM (2013), 457–462.
5. Cohen, J. Defining Identification: A Theoretical Look at the Identification of Audiences With Media Characters. *Mass Communication and Society* 4, 3 (2001), 245–264.
6. Damasio, A. R. *Descartes' error: emotion, reason, and the human brain*. 1994.

7. Dekker, S., Lee, N. C., Howard-Jones, P., and Jolles, J. Neuromyths in education: Prevalence and predictors of misconceptions among teachers. *Front. Psychol.* 3 (2012).
8. Fatourech, M., Bashashati, A., Ward, R., and Birch, G. EMG and EOG artifacts in brain computer interface systems: A survey. *Clin Neurophysiol* 118, 3 (2007), 480–494.
9. Fleck, S., and Simon, G. An Augmented Reality Environment for Astronomy Learning in Elementary Grades: An Exploratory Study. In *IHM '13* (2013), 9.
10. Herculano-Houzel, S. Do you know your brain? A survey on public neuroscience literacy at the closing of the decade of the brain. *The Neuroscientist* 8, 2 (2002), 98–110.
11. Hinckley, K., Pausch, R., Goble, J. C., and Kassell, N. F. Passive real-world interface props for neurosurgical visualization. In *CHI '94*, ACM (1994), 452–458.
12. Horn, M. S., Solovey, E. T., Crouser, R. J., and Jacob, R. J. Comparing the use of tangible and graphical programming languages for informal science education. In *CHI '09*, ACM (2009), 975–984.
13. Lachaux, J.-P., Rodriguez, E., Le Van Quyen, M., Lutz, A., Martinerie, J., and Varela, F. J. Studying single-trials of phase synchronous activity in the brain. *Int. J. Bifurcation Chaos* 10, 10 (oct 2000), 2429–2439.
14. Lehmann, D., Faber, P. L., Tei, S., Pascual-Marqui, R. D., Milz, P., and Kochi, K. Reduced functional connectivity between cortical sources in five meditation traditions detected with lagged coherence using EEG tomography. *NeuroImage* 60, 2 (apr 2012), 1574–86.
15. Mercier-Ganady, J., Lotte, F., Loup-escande, E., Marchal, M., and Lécuyer, A. The Mind-Mirror: See Your Brain in Action in Your Head Using EEG and Augmented Reality. In *VR*, IEEE (2014).
16. Mullen, T., Kothe, C., Chi, Y. M., Ojeda, A., Kerth, T., Makeig, S., Cauwenberghs, G., and Tzyy-Ping, J. Real-time modeling and 3D visualization of source dynamics and connectivity using wearable EEG. In *IEEE Eng Med Biol Soc*, vol. 2013 (2013), 2184–2187.
17. Niedermeyer, E., and da Silva, F. L. *Electroencephalography: basic principles, clinical applications, and related fields*. Lippincott Williams & Wilkins, 2005.
18. Paiva, A., Dias, J., Sobral, D., Aylett, R., Woods, S., Hall, L., and Zoll, C. Learning by Feeling: Evoking Empathy with Synthetic Characters. *Applied Artificial Intelligence* 19, 3-4 (2005), 235–266.
19. Pascual-Marqui, R. Standardized low resolution brain electromagnetic tomography (sLORETA): technical details. *Methods Find Exp Clin Pharmacol* 24D (2002), 5–12.
20. Pfurtscheller, G., and da Silva, F. H. L. Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clin Neurophysiol* 110, 11 (1999), 1842–1857.
21. Piper, B., Ratti, C., and Ishii, H. Illuminating clay: a 3-D tangible interface for landscape analysis. In *CHI '02*, ACM (2002), 355–362.
22. Raskar, R., Welch, G., Low, K.-L., and Deepak, B. Shader Lamps: Animating Real Objects With Image-Based Illumination. In *Rendering Techniques 2001*, S. Gortler and K. Myszkowski, Eds., Eurographics. Springer Vienna, 2001, 89–102.
23. Renard, Y., Lotte, F., Gibert, G., Congedo, M., Maby, E., Delannoy, V., Bertrand, O., and Lécuyer, A. OpenViBE: An Open-Source Software Platform to Design, Test and Use Brain-Computer Interfaces in Real and Virtual Environments. *Presence-Teleop Virt* 19, 1 (2010), 35–53.
24. Shaer, O. Tangible User Interfaces: Past, Present, and Future Directions. *Foundations and Trends in Human-Computer Interaction* 3, 1-2 (2009), 1–137.
25. Simons, D. J., and Chabris, C. F. What people believe about how memory works: A representative survey of the US population. *PloS one* 6, 8 (2011), e22757.
26. Stopczynski, A., Stahlhut, C., Larsen, J. E., Petersen, M. K., and Hansen, L. K. The Smartphone Brain Scanner: A Portable Real-Time Neuroimaging System. *PloS one* 9, 2 (2014), e86733.
27. Tadel, F., Baillet, S., Mosher, J. C., Pantazis, D., and Leahy, R. M. Brainstorm: a user-friendly application for MEG/EEG analysis. *Comput Intell Neurosci* 2011 (Jan. 2011), 879716.
28. Tan, D., and Nijholt, A. *Brain-Computer Interaction: Applying our Minds to Human-Computer Interaction*. Springer-Verlag: London., 2010.
29. Underkoffler, J., and Ishii, H. Urp: a luminous-tangible workbench for urban planning and design. In *CHI '99*, ACM (1999), 386–393.
30. Vosniadou, S. Knowledge Acquisition and Conceptual Change. *Applied Psychology* 41, 4 (1992), 347–357.
31. Vosniadou, S., Ioannides, C., Dimitrakopoulou, A., and Papademetriou, E. Designing learning environments to promote conceptual change in science. *Learn Instr*, 11 (2001), 381–419.
32. Wagner, D., and Schmalstieg, D. Artoolkitplus for pose tracking on mobile devices. In *CVWW '07* (2007), 139–146.
33. Wellington, J. Formal and informal learning in science: The role of the interactive science centres. *Physics Education* 25, 5 (1990), 247.
34. Wilson, A., Benko, H., Izadi, S., and Hilliges, O. Steerable augmented reality with the beamatron. In *UIST '12*, ACM (2012), 413–422.
35. Wolpaw, J. R., and Wolpaw, E. W. *BCI: Principles and Practice*. Oxford University Press, 2012.