BCI and Eye Gaze: Collaboration at the Interface

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Abstract. Due to an extensive list of restraints, brain-computer interface (BCI) technology has seen limited success outside of laboratory conditions. In order to address these limitations, which have prevented widespread deployment, an existing modular architecture has been adapted to support hybrid collaboration of commercially available BCI and eye tracking technologies. However, combining multiple input modalities, which have different temporal properties, presents a challenge in terms of data fusion and collaboration at the user interface. The use of cost-effective and readily available equipment will further promote hybrid BCI as a viable but alternative interface for human computer interaction. In this paper, we focus on navigation through a virtual smart home and control of devices within the rooms; the navigation being controlled by multimodal interaction. As such, it promises a better information transfer rate than BCI alone. Consequently, an extended architecture for a personalised hybrid BCI system has been proposed.

Keywords: Hybrid brain-computer interface · Eye tracking · Domotic control modalities

1 Introduction

Brain-computer interface (BCI) is a paradigm in assistive technology that aims to empower users' capabilities by providing a consistent and reliable input modality that does not require the involvement of peripheral nerves and muscles [1]. In recent years, our increased understanding of the human brain, coupled with advances in modern technology, has led to this type of system becoming a reality, albeit in a more logical and believable form. Whilst the dream of thought controlled devices and applications lives on, the reality, however, focuses on signal processing algorithms that utilise specific patterns in acquired brain signals across both spatial and temporal domains. Increasingly as the algorithms become more complex, the resulting systems may be endowed with more intelligent, contextual processing, thereby leading to increased augmentation for the user.

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While it is possible to monitor this type of brain activity via electrocorticogram (ECoG), functional magnetic resonance imaging (fMRI), magnetoencephalogram (MEG), or near-infrared spectroscopy (NIRS), the most commonly employed approach in BCI is via EEG [2]. In this case, the mental state of the user is stimulated in order to generate brain activity patterns that facilitate control, which will vary in accordance with the underlying BCI operating protocol (also referred to as the BCI *paradigm*) [3]. Commonly employed paradigms include event-related desynchronisation/synchronisation (ERD/ERS), slow cortical potentials (SCP), steady state visually evoked potentials (SSVEP), or the P300 and error-related potential (ErrP) components of event-related potential (ERP) waveforms [4]. Nevertheless, each of these paradigms is hindered by a corresponding set of limitations, including slow information transfer rates, inter/intra-subject variability, inconvenient set up procedures, and the need for carefully controlled environments. This is particularly disappointing as such restrictions adversely affect those that could potentially benefit from this technology the most, individuals who suffer from disease and traumatic injury, which, in severe cases, can lead to Amyotrophic Lateral Sclerosis (ALS) [5]. To reduce the impact of such limitations and utilise the advantages of different BCI methods recent emphasis has been placed upon hybrid architectures. A possible architecture may combine the use of BCI paradigms with separate technologies, such as eye tracking, in order to permit the use of a sequential or collaborative set of input modalities [5]. Systems that follow such a structure are typically known as hybrid BCIs (hBCI) and have the potential to improve classification accuracy for specific tasks, by facilitating individual modalities for distinct aspects of user input processing or cooperative command classification.

In this work, a custom BCI system, originally developed within the EU FP7 BRAIN project to provide BCI control within a virtual domestic environment [6], has been extended to facilitate an approach that makes use of hBCI. Comprising a set of tools for interface development, along with SSVEP and ERD/ERS recording, the system known as the intuitive graphical user interface (IGUI) has been augmented in order to support the combination of eye tracking and BCI control through the use of inexpensive, portable and commercially available devices. Consequently, it is anticipated that the use of such commercially available technology in the hybrid system will facilitate improvements in human-computer interaction over more traditional BCI-based approaches.

2 Related Work

BCI is a potential solution for individuals that suffer from a variation of neuronal dysfunction and similar afflictions, but it endures various technical limitations, which have hindered its exploitation. There is a gap between what is considered to be an acceptable accuracy for a usable system and what is achievable outside the laboratory, in addition to differences in the performance of such systems between users suffering from brain injury and control subjects [6]. Thus, solutions based on hBCI architectures could prove to be the next logical step by harnessing the best features from complementary technologies [5, 7].

Previous research studies have focused largely on singular paradigms in order to facilitate control using BCI systems. Yet these studies have noted accuracy, performance and reliability limitations [8, 9]. The combination of a number of different input modalities may improve upon these results, thus providing a greater level of communication and control [10]. For instance, an active BCI paradigm, such as SSVEP, can deliver a method of direct control, whereas a passive BCI paradigm, such as ErrP, can potentially provide implicit control [11]. Such a system could benefit from reinforced decisions while autonomously correcting false positive *no-control* states, thereby improving upon the performance that the use of a single paradigm can offer [12]. Furthermore, eye tracking technology, which can aid severely disabled individuals by providing them with a level of control, also experiences its own set of limitations. In general, eye tracking, which is often used by patients with peripheral muscular dysfunction, uses both infrared signals and reflected light to determine the trajectory of a user's gaze. This technology is known to provide efficient cursor control but suffers from intended selection restrictions, an area of significant attention in BCI. Earlier research studies have focused on the frequency of blinks and dwell times as the selection criteria, however, the results are far from promising [1], thus increasing the demand for further technological innovation within this area. Subsequently, the collaboration of both BCI and eye tracking as input modalities may mitigate the limitations associated with the individual modalities, thereby providing a more powerful hybrid system. For example, Lee et al. [13] proposed a method to combine BCI and eye tracking for 3D interaction using a bespoke head-mounted eye tracker with attached EEG sensors. According to the experimental results, the feasibility of the proposed 3D interaction method using eye tracking and BCI was confirmed [13]. However, there remains a gap in the efficacy of such systems outside of laboratory conditions, particularly in terms of usability and user interaction [6]. Subsequently, the primary motivation for this research is that solutions based on hBCI architectures could harness features from complementary technologies [5], thereby closing this gap.

3 Navigation and Control of a Virtual Domestic Environment

As previously discussed, the IGUI is a system designed to interact with a virtual representation of a domestic environment, which has the overarching purpose of providing alternative channels for communication and domotic control. The system was originally developed to provide all users with a method to interact with their external environment using a traditional BCI in conjunction with the SSVEP paradigm [6]. Implemented using the Java programming language, thus permitting operating system-independent deployment, the IGUI provides an interactive menu system that has been specifically structured to facilitate four-way directional control and item selection, whereby each selected item controls an event that can be triggered within a corresponding smart environment. As illustrated in Fig. 1, the IGUI presents users with four directional arrows (*Up*, *Down*, *Left*, *Right*), which are utilised to navigate through a hierarchy of environment-related events. The current event, or level of the hierarchy, appears in the middle of the interface, which then permits users to trigger the event,

Fig. 1. The IGUI interactive menu system facilitates domotic control within a smart environment. Navigation through levels of an event hierarchy is conducted though 4-way directional control. A distinct event or current level is positioned in the centre of the interface.

or move to a sub-level of the hierarchy, by selecting the *Down* arrow. Likewise, to navigate to upper levels of the hierarchy, or to exit the system, the user must select the *Up* arrow.

While the IGUI provides the user interface, the overall system has been realised as a customisable and practical application architecture that can be easily extended to support various input modalities. Subsequently, the two primary components of the system are the IGUI and the universal application interface (UAI), which is an application programming interface that provides a generic platform for bridging the IGUI, BCI platform, and both applications and devices within a smart environment.

3.1 Intuitive Graphical User Interface System Architecture

To facilitate BCI-based domotic device control, the UAI interacts with the BCI device through the IGUI. Accordingly, the UAI aims to interconnect heterogeneous networked devices and provide a common controlling interface for the rest of the system. In order to achieve this, UPnP has been chosen as the communication protocol, thus providing an interoperable specification with common protocols to other technologies. As UPnP is a distributed, open networking architecture that uses TCP/IP and HTTP, proximity networking may be enabled in a seamless manner, along with control and data transfer among networked devices. As a result, device interaction with the IGUI system may be implemented through an UPnP interface. Where this is the case, implementation of the UPnP standard will be conducted using a dedicated module in the UAI, which is accessible to all applications. Consequently, the IGUI and UAI interact based upon command structure; in conjunction with both the IGUI and UAI components, the IGUI system architecture utilises a set of user datagram protocol (UDP) packets to facilitate both input and output to/from the overall system. In terms of system inputs, the IGUI has been designed in order to act as a UDP listener. Employing external components to perform processing and analysis of the raw EEG signal, processed signals are translated into directional commands, which are further encapsulated within a set of UDP packets before transmission to the IGUI system. Each packet is assigned an arbitrary code, which is determined in correspondence with the appropriate classification result obtained during signal processing. For example, in the original IGUI system, the SSVEP paradigm was employed to provide four-way directional control in which the *Up*, *Down*, *Left* and *Right* commands were determined from classification of the raw EEG signal. Upon receipt of a UDP packet, the IGUI is updated to reflect the resulting command. In the case where a directional command is used to trigger an environment-related event (i.e. the icon for an event, such as switching on a light, is shown in the centre of the IGUI and the user selects the *Down* command), the command corresponding to the event is processed by the UAI, which, in turn, transmits the command encapsulated in another UDP packet to a UAI receiver for the external device associated with the event. Thus, the IGUI and UAI synthesize in order to facilitate BCI-based navigation and control of devices within a smart environment. However, during initial trials, some users found the use of the directional control system a cognitive challenge as the navigation arrows and manipulation of a central event icon caused confusion and difficulties when attempting to locate specific environment-related events. Additionally, when using the IGUI with a BCI paradigm, several unintended exits would occur due to miss-classification of the raw EEG signal into an *Up* command when the user was at the topmost level of the event hierarchy. Consequently, using alternative input modalities, or hybrid combinations of input modalities, can potentially mitigate the effects of this. In addition, each BCI paradigm utilised with the original IGUI system followed the same command structure and was allocated an individual set of command codes. Although there was no in-built mechanism to automate a switch between paradigms, the modular nature of the IGUI architecture and use of arbitrary codes further promotes development of an hBCI system that can utilise a number of input modalities in either a sequential or collaborative manner.

3.2 Hybrid Intuitive Graphical User Interface System Architecture

In order to provide more intuitive navigation, an eye tracking system was initially implemented whereby a user could select a directional command within the IGUI by navigating to it with their gaze. In keeping with the original design of the IGUI system, the user could then perform selection of an environment-related event using the *Down* command. Essentially, this approach attempts to simulate a more natural input method where the user's gaze acts as both cursor control and mouse click. The eye tribe tracker [14] was chosen as the alternative input modality because it is available at a much lower cost than other eye tracking systems, and yet it retains sufficient accuracy for this type of application. At first glance, the eye tracking-only variation of the IGUI system appeared to significantly outperform the original BCI-only variation in terms of accuracy of user control. However, after extensive testing, a substantial rate of false positives was detected, especially when a user paused to think, as this often resulted in excessive dwell times occurring on targeted directional commands, which substantially reduced the reliability and usability of the system.

To overcome this issue, a further iteration of the IGUI system was developed to integrate a brain-neuronal computer interaction approach, thereby permitting inclusion of devices that monitor additional physiological signals, not only from signals acquired directly from the brain. Utilising the Emotiv EPOC [15] as a BCI device for the acquisition of EEG activity, it was possible to mitigate the dwell time with a teeth clench component as a proxy for an EEG feature, which was subsequently employed to trigger usage of the eye tracker component. The EPOC was employed to extract the representative features from scalp locations AF3, AF4, F3, F4, F8, F7, FC5, FC6, T7, T8, P7, P8, O1, and O2. In order to extend the base IGUI architecture, a *Data Fusion* component was implemented within the IGUI, which was responsible for determining an authoritative control signal from the receipt of UDP packets from both the BCI device and eye tracker. An overview of the data flow through the various components of the IGUI system is illustrated in Fig. 1.

In terms of multimodal interaction, the current system supports two modalities for selection and control. The eye tracker can facilitate navigation and selection by generating a set of co-ordinates that are representative of the users gaze, divided among the four quadrants of the IGUI. In the centre of the IGUI is a *No State Zone*, which is a predefined location where the user can verify selection of an environment-related event. Additionally, the BCI device can facilitate explicit operation of the eye tracker by permitting the user to initiate and suspend use of the eye tracker when required. In essence, the BCI device acts as a *switch*, therefore simple EEG-based features, such as an increase in overall EEG power initiated by the user, can be potentially utilised. Correspondingly, more sophisticated features can be initiated by relaxation (e.g. an increase in the alpha activity ratio of the EEG signal) or in response to screen-based visual stimulation, such as the use of a pattern reversal stimulus at a pre-determined frequency, thereby invoking an SSVEP response. As the IGUI system must also handle quickly repeated correct commands, due to variations in the frequency of responses from the individual input modalities, in conjunction with the variable nature of user interaction, the frequency of the response from the eye tracker has been reduced in order to moderate responsiveness. The following sections of the paper cover details of the experimental protocol used and analysis of the corresponding results from testing of both the eye tracker-only and hybrid variations of the system (Fig. 2).

4 Methodology

Within the BCI literature it is common to measure performance by calculating the information transfer rate (ITR) in bits/min, which takes into account values for both accuracy and time. Accordingly, the literature suggests that BCI systems generally

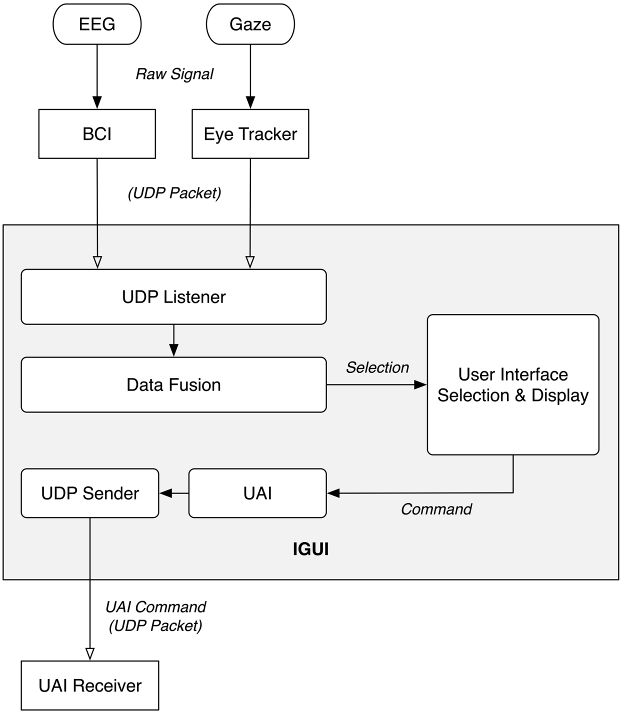

Fig. 2. The internal dataflow of the hybrid system featuring a BCI-based input modality and an eye tracking input modality.

achieve an ITR between 10–25 bits/min whereas conventional input devices, such as a mouse and keyboard, have been known to achieve an ITR in excess of 300 bits/min. ITR as defined in [16] is shown below:

$$ITR = (log_2 M + P log_2 P + (1 - P) log_2[(1 - P)/(M - 1)]) * (60/T). \quad (1)$$

where M is the number of choices, P is the accuracy of target detection, and T is the average time for a selection. Subsequently, this metric has been used in order to conduct an evaluation of the performance of the two variations of the IGUI system. A cohort of 12 users were asked to carry out 3 tasks within the associated virtual domestic environment, as follows:

Task 1 (Domotic Control): The purpose of this task is to simulate navigation and control within the virtual domestic environment. Starting in the Back Garden, the user is asked to navigate to the Dining Room, turn on a lamp, and then return to the Back Garden. The sequence of sequential operations required to successfully perform this task is as follows:

$$Right \rightarrow Right \rightarrow Right \rightarrow Right \rightarrow Down \rightarrow Right \rightarrow Right \\ \rightarrow Down(LampON) \rightarrow Up \rightarrow Left \rightarrow Left \rightarrow Left \rightarrow Left$$

Task 2 (Multimedia Control): Similar to Task 1, the purpose of this task is also to simulate navigation and control within the virtual domestic environment. For successful completion of this task, the user was required to start in the Back Garden, then navigate to the Living Room, select the Living Room icon in order to enter the corresponding level of the event hierarchy, navigate to and select the Home Media icon, navigate to and select the Home Cinema icon, navigate to and select a Video icon in order to start playing a video, return to the Home Media icon, navigate to and select the Controls icon, navigate to and select the Stop icon in order to stop playing the video, then return to the Back Garden. The sequence of sequential operations required to successfully perform this task is as follows:

$$Left \rightarrow Left \rightarrow Left \rightarrow Down \rightarrow Left \rightarrow Down \rightarrow Right \rightarrow Right \rightarrow Down \\ \rightarrow Right \rightarrow Right \rightarrow Right \rightarrow Down(Play) \rightarrow Up \rightarrow Left \\ \rightarrow Left \rightarrow Down \rightarrow Right \rightarrow Down(Stop) \rightarrow Up \rightarrow Up \rightarrow Up \\ \rightarrow Right \rightarrow Right \rightarrow Right$$

Task 3 (Communication): Similar to the previous two tasks, the purpose of this task is also to simulate navigation within the virtual domestic environment, however, rather than direct selection of an environment-related event, the user is asked to indicate their desire to eat using the iconography provided within the environment. For successful completion of this task, each user was required to start in the Back Garden, then navigate to and select the Talk icon, navigate and select the Eat icon, then return to the Back Garden. The shortest series of sequential operations required to successfully complete this task is follows:

$$Left \rightarrow Down \rightarrow Left \rightarrow Left \rightarrow Down(Eat) \rightarrow Up \rightarrow Right$$

For both variations of the IGUI system, the ITR was determined according to Eq. (1) for individual users on each task.

5 Evaluation Results

A comparison of the mean ITR values from each task using both variations of the IGUI system is given in Fig. 3. In order to determine the mean ITR for each task, the ITR from each task for each user was first determined and the overall set of ITR values for a task averaged. Subsequently, when Task 1 was carried out using the eye tracker-only variation of the IGUI system, a mean ITR of 122.79 (SD: 28.53) bits/min was obtained, whereas a mean ITR of 168.70 (SD: 21.17) bits/min was obtained for Task 1 when the hBCI variation of the IGUI system was used. Likewise, Task 2 also showed an increase

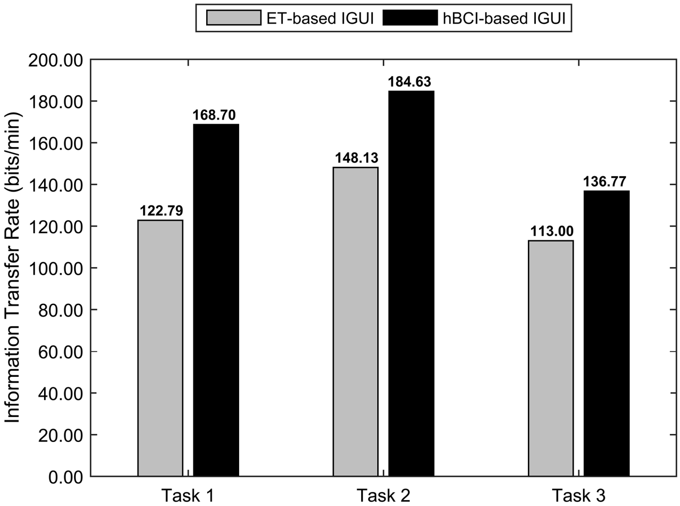

Fig. 3. Comparison of mean information transfer rate values for each task performed by all users when utilizing the eye tracker-only version of IGUI system (denoted *ET-based IGUI*) and hybrid version of IGUI system combining eye tracker for directional control and EEG-based signal for switch (denoted *hBCI-based IGUI*).

in the mean ITR obtained, from 148.13 (SD: 14.98) bits/min, when using the eye tracker as the only input modality, to 184.63 (SD: 25.05) bits/min when using a combination of eye tracking and an EEG-detected teeth clench as input modalities. The improvement in the ITR is also observed for the results obtained from Task 3, with the single input modality achieving a mean ITR of 113.00 (SD: 22.27) bits/min in comparison to the combination of input modalities, which achieved a mean ITR of 136.77 (SD: 18.02) bits/min. Consequently, the results indicate that regardless of the complexity of the task, a higher ITR is achieved when utilising a combination of an eye tracker for directional navigation and selection, and a BCI-based switch to trigger the use of the eye tracker, as input modalities.

During the evaluation of the eye tracker-only variation of the IGUI system, a number of false positives were detected, which triggered an incorrect command that needed to be rectified by the user, or in the case of an unintended exit, by the experimenter. In the cases where an unintended exit occurred, the interaction time was paused and the IGUI manually returned to the state prior to the unintended exit. All unintended commands were considered as false positive commands and any commands used to rectify a mistake were considered as true positive commands, which were factored into the calculation of the individual ITR values.

By contrast, during evaluation of the hybrid variation of the IGUI system, a significant reduction in the number of false positive commands was observed. As a result, no unintended exits were triggered by any of the users during the evaluation. However, unintended commands still needed to be rectified by the user. In addition, the hybrid system also experienced a rate of false negatives, which were not present during the evaluation of the eye tracking-only version of the system. As false negatives do not trigger incorrect commands, these were considered as tolerable. Nevertheless, all such erroneous commands were factored into the calculation of the individual ITR values.

6 Discussion

A potential solution to this type of human computer interaction is to produce a fully open source system that incorporates inexpensive and commercially available eye tracking and BCI hardware. Although such components may not meet the performance of research-grade devices, they should be sufficiently accurate to provide the desired level of control. By utilising devices such as the eye tribe tracker and emotiv EPOC collaboratively within hBCI architectures, it is potentially possible to more effectively deploy such systems outside of the laboratory environment.

In order to move towards more personalised hBCI architectures, the IGUI system could be further expanded to incorporate a range of additional input modalities. Subsequently, all chosen modalities should permit unique interactions with the IGUI and be eventually handled by the *Data Fusion* component in order to influence user commands. Furthermore, modalities should be weighted by the *Data Fusion* component and operate either collaboratively or competitively, whereby weightings are automatically adjusted as the system is utilised in order to provide a degree of personalisation. Moreover, in order to further expand and exploit the IGUI system architecture, two key application domains should be taken into consideration: affective computing and ambient intelligence. Subsequently, Fig. 4 illustrates a proposed personalised hBCI architecture that utilises the IGUI as a core component.

As depicted in Fig. 4, integration of an affective computing sensor platform would facilitate input to the IGUI from a range of pre-processed features acquired by physiological and affective sensors, in conjunction with the use of passive BCI. By passively monitoring physiological and emotion-related signals, including the EEG signal, the

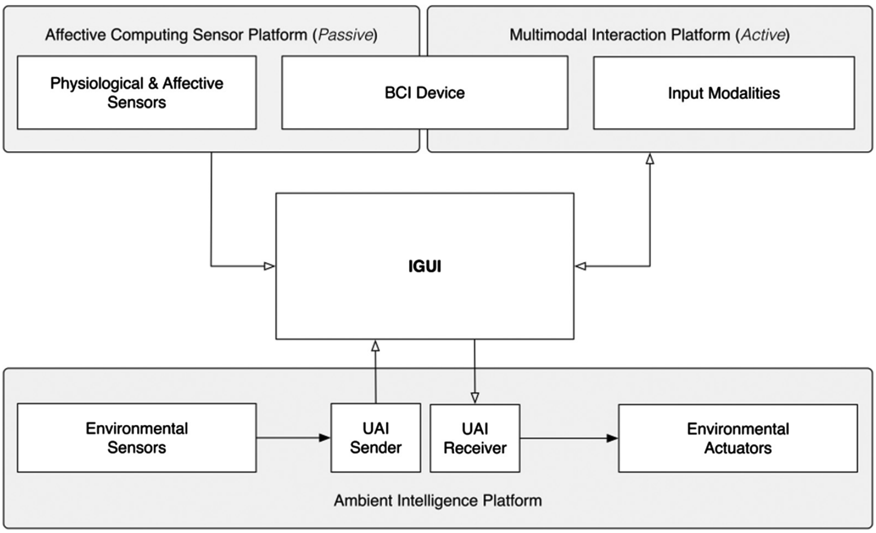

Fig. 4. A proposed architecture for personalised hybrid BCI that expands on the IGUI system

resulting affective state of a user may be determined and subsequently utilised by the IGUI in order to permit a degree of personalisation and system adaptation [17, 18], through the weightings and control signals associated with the data fusion component of the IGUI. In essence, the affective computing sensor platform, in conjunction with usage statistics from the IGUI, could be used to generate an affective model of the user, which acts as an enabler for personalisation of the overarching user interface and set of input modalities. Additionally, the ambient intelligence platform may be used to facilitate feedback of external environmental information to the IGUI. Such feedback, in conjunction with the IGUI usage statistics, could potentially provide a further degree of contextual information that could subsequently be utilised to provide enhanced context awareness that contributes to the adaptation of the IGUI and choice of input modalities. For example, menus within the IGUI could be arranged according to frequent usage depending on current tasks, historical patterns, time of day, etc. Again, this leads to a greater degree of personalisation, as the iconography employed within the IGUI could be adapted to support the current context of the user. Furthermore, a hBCI system that utilises the collaboration of active BCI, eye tracking and other technologies as input modalities may be employed to provide a multimodal interaction platform that mitigates the limitations associated with these individual modalities, thereby providing a more natural set of active inputs for the personalised hBCI architecture.

7 Conclusion and Future Work

In this work we have shown the feasibility of using collaborative input modalities based on a hybrid BCI approach. Both of the devices utilised are cost-effective, highly usable and sufficiently accurate, which makes them particularly suited for deployment outside of laboratory conditions. A benefit of such a hybrid approach is in the system's ability to facilitate interaction only when desired by the user, rather than unintentionally when the user is distracted or idle. In the evaluation presented, we have also shown that the fusion of BNCI and eye tracking technologies improves upon the performance of singular approaches. Consequently, a key objective for future work is to investigate how the current BNCI component can be replaced with the use of more traditional BCI paradigms. Furthermore, an extended hybrid architecture has been proposed, which substantially expands upon the range of input modalities to incorporate environmental, physiological and affective features, thus facilitating the creation of a truly personalised hybrid BCI system. It is anticipated that collaboration at a central interface will enfranchise such personalisation.

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