Sensorimotor-rhythm Modulation Feedback with 3D Vector-base Amplitude Panning – A Brain-Computer Interface Pilot Study

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***Abstract*— A sensorimotor rhythm (SMR) brain-computer interface (BCI) not reliant upon the visual modality for feedback is desirable. Feedback is imperative to learning in a closed loop system and in enabling BCI users in learning to module their sensorimotor EEG rhythm. This pilot study demonstrates the feasibility of replacing the traditional visual feedback modality with a novel method of presenting auditory feedback: 3D vector-base amplitude panning (VBAP). Auditory feedback not only releases the visual channel for other uses but also offers an alternative modality for the vision impaired. 3D VBAP is compared with auditory feedback presented monaurally and stereophonically. VBAP feedback is presented in the form of an auditory asteroid avoidance game. This pilot study included two participants who demonstrate well above chance level that sensorimotor modulation is possible using all three presentation methods with VBAP, mono and stereo performing from best to worst respectively. Although the results are confounded by the number of subjects and sessions involved, this pilot study demonstrates for the first time that 3D VBAP can be used for SMR feedback in BCI and that users find it more appealing than other auditory feedback approaches.**

***Keywords* – brain-computer interface, sensorimotor rhythms, audio feedback, vector-base amplitude panning**

I INTRODUCTION

A brain-computer interface (BCI) is a device used to translate the brainwaves of a user into commands interpretable by a computer, bypassing the usual muscular channels. BCIs can therefore offer alterative communication mechanisms to those with neuromuscular disorders. One such clinical group are motor neurone disease (MND) sufferers whose illness has progressed to a phase where they are considered to have reached a locked-in stage whereby they are no longer able to communicate or interact with their surroundings.

A user has the ability to modulate the amplitude of their sensorimotor rhythms (SMR) by performing motor imagery (movement imagination) and this is the basis of SMR-based BCI. Feedback is essential in learning within in a closed-loop system and is especially important in learning to affect the SMR. However, this feedback is most commonly presented using the visual channel and unfortunately, this can exclude potential recipients of the technology such as those with vision problems and also interfere with the use of other assistive devices e.g. wheelchair control, graphical user interface (GUI), etc.

Amyotrophic lateral sclerosis (ALS) is a disease where the sufferers may find the greatest benefit from the technology as ocular instabilities have been shown to exist in sufferers not only in the latter stages of the disease but also during the onset [1][2]. However, these account for just a minority of beneficiaries. Others may also benefit from the research such as the able bodied, spinal cord injury (SCI) patients and blind or partially sighted individuals. Indeed, it is estimated that by 2050 there will exist almost four million people in the U.K. whose sight will be compromised due largely to the ageing population [3].

While a number of BCI systems exist which are based upon the use of the auditory channel, it is important to make the distinction at this point between the presentation of audio as either a stimulus or as a feedback mechanism.

a) Audio Exogenous BCI

Exogenous BCI involve eliciting a brain response via an external stimulus and have been the basis of a number of BCI studies. Höhne et al. [4] used the auditory P300 response in a 3x3 matrix or 9 class model to design a T9 texting style spelling system. Both lateral position and pitch were used to induce an event related potential (ERP) and found that a lower pitch would lend to a higher selection accuracy achieving an average of 3.4 bits/min. Halder et al. [5] support these findings in their study on the effect of varying auditory stimulus parameters such as frequency, direction and amplitude. A multi-class P300 spatial auditory BCI was proposed in [6], involving the use of multiple loudspeakers to present audio stimuli. Speakers placed behind the listener were omitted as these were frequently confused with frontally located speakers; a problem which was solved in [7] using an empirical mode decomposition (EMD) and novel "*steady-state tonal frequency stimuli*" method.

b) Audio Endogenous BCI

Endogenous BCI are reliant upon the user to perform a mental task in order to effect a change in their brainwaves without the aid of an external stimulus. Pham et al. [8] presented auditory feedback of slow cortical potentials (SCP) where they examined subjects divided into audio, visual or audio/visual feedback groups. They concluded that although the visual group performed better, the auditory group were also able to use the system successfully. They attribute the difference in each group's performance to biophysical shortcomings and the fact that the auditory feedback may have been too difficult to interpret.

A SMR BCI using auditory feedback was examined in [9] again dividing subjects into visual and auditory feedback groups. A psychological study was also carried out which served to evaluate each person's mood and motivation preceding each session. The feedback used in their study assigned one of two sound effects to each class which seems unnecessarily complex and may be improved upon.

In [10] the effectiveness of stereo auditory feedback and its visual equivalent were compared. Broadband pink noise was presented in a modified stereophonic speaker arrangement to allow listeners to intuitively assign each of two classes to the corresponding direction: left imagery would cause the feedback to move toward the left-hand side and vice versa. Broadband noise contains sufficient cues both above and below 1.5kHz which are necessary for effective localisation of audio [11]. Results were promising with the highest performing participant overall being part of the auditory group.

c) Motivation and BCI Games

In order to use an SMR-based BCI training is required. This can take days or weeks in the case of some individuals and hence motivation is important in these cases. In fact, motivation has shown to be a crucial factor in the success of BCI participants [10][11]. As some training paradigms can become tedious for participants over time, any mechanism which encourages the user to spend longer using the system is desirable. Hence, the field has begun to witness the emergence of a number of BCI gaming devices with the aim of increasing interest and motivation levels. Needless to say, the games industry also has a vested interest in BCI as an additional method of control.

d) Vector-base amplitude panning

3D vector-base amplitude panning (VBAP) [14] is a technique which uses multiple speakers to position a virtual sound source around the listener and does not limit the sound to a vector between two locations as does stereo reproduction. The use of just two speakers also restricts stereo auditory reproduction to two dimensions whereas multi-speaker 3D VBAP allows for the height dimension to be reproduced. VBAP allows for speakers to be placed somewhat arbitrarily and is hence suited for placement within the restricted confines of a small BCI laboratory. It also allows for a richer listening experience and more closely represents the natural listening environment we experience in the real world.

This pilot study seeks to assess the feasibility of using 3D VBAP feedback for the control of a SMR based BCI. The feedback is presented in one of three forms to compare effectiveness: monaural (mono), stereophonic (stereo) and using VBAP to present an Asteroids-like auditory game where the aim is to avoid falling asteroids and accumulate points over time. This mimics studies which have taken place at the research centre [15] but which have previously involved visual feedback (http://www.youtube.com/user/BCiCONCISE).

II METHODS

The pilot study involved just two male participants with normal sight and hearing and both of which were experienced BCI users. Each took part in three sessions involving 4 runs of 60 trials per session, a training run with no feedback, a mono feedback run, a stereo feedback run and VBAP run. A training run containing 60 trials each lasting 7 seconds in addition to an inter-trial interval lasting between 0-2s used in order to avoid adaptation. Further details of the timings involved can be viewed in Figure 1. The timings used in the session closely mimic those of visual feedback BCI experiments commonly used. Subjects were seated in a chair approximately 1.5m from a wall upon which a cross was presented. The user was asked to focus on this to discourage their gaze from wandering. Loudspeakers were placed at various angles from the listening position, the placement of which were dependent upon which run they were taking part in.

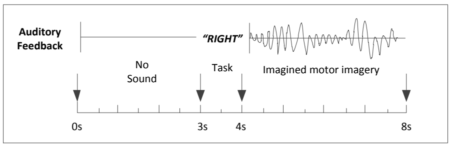

Figure 1: Trial timings

a) EEG Recording

As the system is based upon the imagined movement of left and right arm, sensorimotor rhythm activity is typical measured over the motor cortex and hence electrodes were placed over C3, C4 and Cz in a bipolar configuration with the reference taken from Fpz. The g.GAMMAsys active electrode cap system (www.gtec.at) was used to measure EEG in conjunction with the g.BSamp. Signals then passed to a data acquisition PCI card from National Instruments for digitisation at 125Hz.

b) BCI

The BCI translation algorithms running in MATLAB and Simulink are based upon the work in [13][14] a short description of which now follows. The EEG signals first pass through a prediction based pre-processing stage where specialised networks are trained to predict future samples, with the consequence that features contained in the output are more separable than those in the input signals allowing for easier classification. The network adapts autonomously to each individual's data using self-organising fuzzy neural networks (SOFNN). Spectral filtering then takes places in subject-specific sub-bands. The μ and β bands are most commonly modulated during motor imagery and lie between 8-28Hz where particle swarm optimisation is used to find the optimal subject specific band. Common spatial patterns (CSP), a method which maximises the difference in class conditional variances, is then employed to further improve data separability. The log-variance is then taken of the pre-processed signals using a 2s sliding window and is the basis for feature extraction with linear discriminant analysis (LDA) used to classify the features.

c) Training run

For the training run in each session two loudspeakers were incorporated with one placed at -90° azimuth (θ) and 0° elevation (ϕ,) or directly facing the left ear, and one at 90° θ and 0°ϕ, or directly facing the right ear (Figure 2) at a distance of approximately 60cm. The timings of the trials, demonstration graphics and audio playback were coded using Microsoft's XNA game development platform and communicated with the BCI running on MATLAB/Simulink over a network using the user datagram protocol (UDP).

d) Feedback runs

Each of the three feedback runs presented the participant with a different method of auditory feedback. Each of these methods was presented in a different order during each session so as not to allow for any one run to receive more training time than any other run.

For the ***mono feedback*** run, audio was presented using the same speaker arrangement used for VBAP feedback described later, that is, audio was presented in equal volume from all directions simultaneously. Each target direction was assigned a tone; 400Hz for left and 1478Hz for right. Feedback was given using a resonant filtered continuous pink noise. The filter's centre frequency was limited between 400-1478Hz and was a translation of the time-varying-signed distance (TSD) [18] output from the classifier. Hence, imagination of left arm would cause the feedback to move towards the lower end of the spectrum and vice versa for right arm motor imagery.

For the ***stereo feedback*** session, audio was presented with the loudspeakers positioned as in the training run (Figure 2). The target was a spoken command of "left" or "right" originating from the corresponding direction followed by pink noise for the remainder of the imagination period. Imagination of the left arm would cause the audio to pan towards the left hand side in a continuous transition and vice versa.

Figure 2: Training and feedback loudspeaker setup

Three dimensional VBAP is a method of positioning an audio source within a 3 dimensional space and is used in this study with 8 loudspeakers positioned in an approximately hemispherical arrangement around the listener (Figure 3). Placements of loudspeakers were limited somewhat by the size of the laboratory and were placed at the following locations: -90°θ 50°ϕ, -90°θ -32°ϕ, -45°θ 0°ϕ, 0°θ 50°ϕ, 0°θ -32°ϕ, 45°θ 0°ϕ, 90°θ 50°ϕ, 90°θ -32°ϕ at an approximate distance of 110cm from the listening position.

Figure 3: VBAP speaker arrangement for mono feedback and auditory Asteroids game

The aim of the game was to dodge asteroids which appeared from above the listener's head as they fell toward the ground. A visually equivalent model is first shown to the participant in order to ensure they fully understand the principals involved (Figure 4).

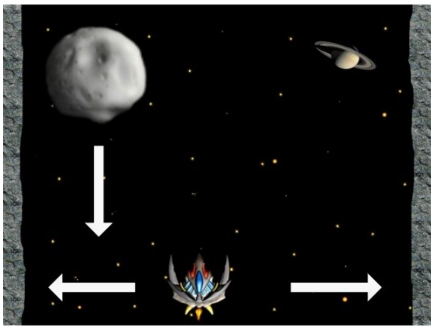

Figure 4: Auditory Asteroids game visual representation

The sound used for the asteroids was created using the free audio editing program Audacity (http://audacity.sourceforge.net) and consisted of a sine wave swept exponentially from 800Hz to 300Hz over 6s and combined with 1/f or pink noise. This was then processed with an inverse sawtooth tremolo effect at 7.5Hz. It was hoped that this sound would give the impression of an object falling whilst also ensuring it contained enough cues both above and below 1.5kHz which are essential for effective sound localisation [11]. Imagination of the left hand would cause the listening position to shift to the left and conversely imagination of the right hand would cause the listening position to shift towards the right. As in the stereo feedback paradigm the amount of movement in each direction was indicative of the TSD of the classifier. If the user was successful in avoiding the asteroid they would hear it pass by them on each side; if not, then an explosion was heard to indicate a collision.

As continuous control over the feedback was given during the game it was difficult to determine when the extreme of each direction was reached and so an audio beacon was introduced which served to reinforce the target direction. The beacon consisted of a 1000Hz sine wave pulsing at 4Hz and again combined with pink noise to aid localisation. Whilst the audio was controlled from XNA in the training run, Max/MSP (www.cycing74.com) was used for the feedback sessions to produce a multiple speaker output. Max/MSP communicated with XNA via UDP which received data on target direction, listener and asteroid position. The Ultralite Mk3 from MOTU was used as the audio interface as it is capable of operating in a low latency mode which in turn fed each of the 8 separate M-Audio AV20 powered speakers.

III RESULTS

A chance level of 50% should only be used with a confidence interval when considering a two class classification problem, according to [19]. Therefore, with 30 trials per class and a confidence interval $\alpha = 0.01$, 67.5% more closely describes chance level accuracy [19].

The classification accuracy (CA) results, calculated using 5-fold cross validation, for each participant in every run, are presented for participant **A** (Table 1) and participant **B** (Table 2). Both participants were able to use the system with greater than 70% accuracy in every feedback run but one, even though participant A obtained just 58.57% CA in their first training session. The average of both subjects CA for each feedback type indicates that VBAP was the most effective method at 81.39% followed by mono at 80.17% with stereo giving 78.89% however due to the limited number of subjects and sessions involved in the study these results are not conclusive as to which feedback method is best.

Table 1: Participant A classification accuracy (%)

Session No.	Training	Mono	Stereo	VBAP
1	58.57	76	70	71.67
2	76.67	81.67	81.67	83.33
3	80	75	73.33	73.33
Mean	**71.75 ±9.42**	**77.56 ±2.94**	**75 ±4.91**	**76.11 ±5.15**

Table 2: Participant B classification accuracy (%)

Session No.	Training	Mono	Stereo	VBAP
1	70	81.67	66.67	83.33
2	88.33	83.33	90	95
3	86.67	83.33	91.67	81.67
Mean	**81.67 ±8.23**	**82.78 ±0.78**	**82.78 ±11.4**	**86.67 ±5.93**

IV DISCUSSION AND CONCLUSION

This pilot study set out to assess the feasibility of using VBAP feedback to control a SMR BCI. Both participants reported that VBAP was the most pleasant to use and found the other feedback methods tedious which was to be expected, as there was not enough variation in the sound to keep their interest. Both were able to use the system with a reasonable level of control. Nevertheless, some improvements to the system are recommended before beginning a large cohort study. Mono feedback was found to be difficult to interpret and may have resulted in incorrect imagination at times. Also, subjects reported during the VBAP session that the sound of the beacon and the sound of the asteroid were too similar and hence were difficult to differentiate early in the trial and therefore it will be necessary to adjust the audio accordingly. The loudspeaker placement during the stereo feedback session was chosen to give the widest possible image and although this was achieved, it provides the listener with a distinctly unnatural "*inside-the-head-locatedness*" [11] sensation when listening to audio which does not occur during the VBAP presentation.

As mentioned, results from a previous study [10] including 20 subjects who took part in 10 sessions, showed that auditory feedback is a viable alternative to the visual equivalent. However, the benefits of using spatial audio will be examined more thoroughly in further studies as participants will also be asked to complete a questionnaire examining their experiences on each feedback type. This should hopefully allow for a better insight into each participant's motivation levels which, as mentioned previously, are important in BCI training.

An extended study is already planned which will make use of 5 new participants each of whom will take part in 20 sessions, 10 sessions in which they will receive visual feedback and 10 in which they receive only auditory feedback in order to more accurately compare the two feedback mechanisms and assess the significance of the methods presented. It is expected that the spatialisation of audio for feedback using VBAP will improve the listening experience for the user and improve accuracy over time.

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