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A smartphone-based platform for portable, non-invasive, audio and visual neurostimulation with a non-rhythmic sham stimulation mode

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***Abstract*— Non-invasive neurostimulation is an emerging approach for chronic pain management, working by applying a flashing visual stimulation in the 10 Hz range, or via binaural beats were tones, differing by approximately 10 Hz, are played to each ear. Our previous work has presented smartphone based delivery of audio and visual stimulation, with smartphones being selected as a form factor which is portable, easy and convenient for people to use in home-settings, and readily integrated into body sensor network deployments. However, this did not include a sham stimulation mode allowing control studies to be performed. This paper presents a second generation Android smartphone App for providing non-invasive audio and visual stimulation. A sham mode is added via non-rhythmic neurostimulation, jittering the instantaneous stimulation frequency. Hardware characterization and computational cost measurements demonstrate the high accuracy and efficiency of stimulation generation.**

I. Introduction

Body sensor networks have been widely used for sensing applications, allowing large scale data collection using wearables, smartphones, and other low power devices. There is now substantial interest in moving beyond only *sensing* applications to *sensing and actuating* applications, giving devices which can provide feedback and stimulation to users [1], [2]. One potential application where intervention can be given via a smartphone is in chronic pain.

Chronic pain affects approximately 20%–40% of the world's population, and severely degrades peoples' quality of life. [3], [4]. Conventional management approaches, such as opioids or non-steroidal anti-inflammatory drugs, are not always adequately effective and may cause a variety of side effects [4]. As a result, alternative pain management approaches are being actively researched. In particular, non-pharmacological approaches have been increasingly investigated in recent years [4], [5].

Non-pharmacological approaches which have received substantial attention are neurostimulation and neuromodulation: an intentional modification of brain activity by applying an external, and usually rhythmic, stimulus [5]. As a technology driven, potentially non-invasive, approach, neurostimulation and neuromodulation offer an *electro-ceutical* approach to complement and augment traditional pharmaceutical approaches. For example, our previous work has found that increasing brain activity in the alpha (8–13 Hz) range reduced pain as reported on a visual analogue scale [6]–[8].

In recent years we have focused on delivering this brain stimulation via audio and visual means as these are non-invasive, and readily implemented into smartphones and body sensor networks, making them potentially suitable for at-home use and integration into body sensor networks [2], [9]. Acoustic stimulation can be achieved via Binaural Beats (BB), in which tones with slightly different frequencies are played to each ear via stereo headphones, resulting in brain synchronization to the difference of frequencies played [10]. Visual stimulation can be achieved via flashing the smartphone screen to create Steady-State Visual Evoked Potentials (SSVEPs) [11].

However, our previous stimulation platform, reported in [2], lacked a *sham* mode that could deliver stimuli for investigating the placebo effects, for example, placebo analgesia, in chronic pain. As reported in [5], [12], neurostimulation approaches may lead to powerful placebo effects to pain relief due to psychological factors, such as user expectations towards highly specialized technology and the enablement of more interactions between patients and physicians offered by remote digital care. Therefore, systematic studies towards placebo effects in chronic pain via sound and visual stimulation are required.

For non-smartphone based stimulation, Table I illustrates example sham modes used to date. For BB sound stimulation, studies in [6], [13]–[18] adopted white noise, music, monotone, and silence as their sham stimulations. However these can be easily differentiated from the real stimulation modes by users. Similarly, [6], [7] used 1 Hz and 7 Hz as the sham stimulation, which may result in delta (0.5-4 Hz) and theta (4-8 Hz) activities to be enhanced, and can be visually distinguished from the wanted 10 Hz stimulation. Therefore, currently, there remains a technical challenge on how to create effective sound/visual sham modes that are not readily distinguished from the wanted stimulation, and to implement the chosen approach on a low power smartphone based platform.

This paper presents a new smartphone platform for delivering sound and visual stimulation at 10 Hz, and also providing sham modes. Two sham modes are included: (1) Near-monotones for sound stimulation, and (2) Randomized and non-rhythmic flickering light for visual stimulation. This offers a more complete on-phone experimental platform. Hardware characterization to validate the accuracy of the smartphone App and computational cost tests are included to demonstrate its rapid processing and low power consump-

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TABLE I

SUMMARY OF ACTIVE MODE SHAM METHOD APPROACHES IN SOUND AND VISUAL NEUROSTIMULATION

	Ref	Target application	Active mode	Sham mode
Sound stimulation	[6]	Chronic pain	8/10/12 Hz BB	White noise
	[13]	Chronic pain	Meditation music with a simple BB overlaid	Music
	[14]	Sleep and pain	alpha/theta/delta BB	Monotone below 1 Hz
	[15]	Sleep	6 Hz (theta) BB	Music
	[16]	Sleep	BB with pink noise background	Monotone with pink noise
	[17]	Sleep	6 Hz (theta) BB	Silence
	[18]	Cardiovascular stress response	Music with BB	Music
Visual stimulation	[6]	Chronic pain	8/10/12 Hz flickering	1 Hz flickering
	[7]	Chronic pain	10 Hz flickering	7 Hz flickering

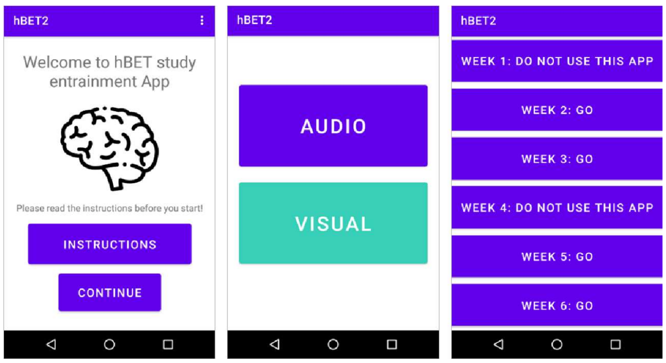

Fig. 1. A screenshot of the App. Homepage (left), Mode selection page (middle), and an example of a double-blind experiment scheme (right).

tion.

II. METHODS

A. Development platform

Our App was developed in the Android Studio IDE, based on our previous work in [2]. Sound and visual stimulation were designed as an open-loop system in which the stimulation parameters are pre-programmed in advance. A Samsung Galaxy A40 smartphone (octa-core Exynos 7904 processor with 4GB RAM, 60 Hz screen refresh rate) was used for the App test and validation in this work. A screen shot of the App is shown in Fig. 1.

B. Sound stimulation

The Binaural Beats (BB) sound stimulation was implemented by using the AudioTrack class in Android. The sampling frequency was set at 44,100 Hz, and then two pure sine waves with different frequencies generated in real time to be streamed to the different ears. The tones are continuously produced and played inside an infinite loop until stopped by the user.

1) Active mode: For generating the active BB stimulation at 10 Hz, we created a tone at 400 Hz which is constantly played via the left ear and set the tone at 410 Hz for the right ear. 10 Hz was chosen as the target stimulation frequency as it is the middle value of the EEG alpha range (8–13 Hz) and has been commonly used in previous works [6]–[8]. The settings are not user programmable, but can be readily changed in the underlying App programming if required.

2) Sham mode: Sham mode stimulation was created by setting up 400 Hz and 400.01 Hz BB, so the target stimulation frequency is at 0.01 Hz, out of the range of the EEG frequencies, and thus it should not affect brain activities in other frequency ranges. This sham mode sounds like a monotone, which is much closer to BB compared to white noise, music and silence acoustically, making it harder to be distinguished by users.

C. Visual stimulation

Visual stimulation was achieved via flickering the smartphone screen at a fixed frequency using the OpenGL graphics library. The screen flicker works by rendering the current frame as white and black colors in turns according to the desired frequency. The smartphone used currently could generate 1–20 Hz screen flickers based on the algorithm presented in [2] on a smartphone with a 60 Hz refresh rate. Note current state-of-the-art smartphones normally have 90/120/144 Hz refresh rates which could be used for producing visual stimulation schemes at higher frequencies, although the use of dynamic refresh rates may complicate this.

1) Active mode: The active stimulation mode was set to flicker the screen constantly at 10 Hz until stopped by the user.

2) Sham mode: For sham stimulation we required screen flickering not at a fixed 10 Hz, but also not at a fixed alternative frequency which might entrain the brain at that frequency. We opted for a non-rhythmic approach, keeping the average instantaneous stimulation frequency at 10 Hz to keep the visual perception similar, while the actual instantaneous stimulation frequency varies on a second-by-second basis. This is achieved by using a Random Object which randomly picks a number from an integer array range from 5 to 15 every second, then the screen flashes at the random frequency (5–15 Hz) and updates for every second. This is similar to the jittered sham stimulation in [19], but implemented on a smartphone platform for the first time.

D. Other functions

The App can be programmed to randomize the active stimulation and sham mode in different orders as desired by researchers to enable different double-blind crossover experiments.

E. Stimulation characterization

1) Audio mode validation: To measure the tone frequencies for the audio mode, the smartphone headphone output was connected to a myDAQ Data Acquisition device (National Instruments Inc., USA) via a 3.5 mm stereo audio cable. The generated tones were then played and LabVIEW software was used for measuring and displaying the power spectrum of the analogue audio signal.

2) Visual mode validation: To test the accuracy of the visual stimuli generated, a spectrometer (AS7341 Evaluation Kit, ams OSRAM Inc., Austria) was placed on top of the screen and used to measure the frequencies of the screen flickering. Specifically, for validating the sham mode, the instantaneous frequency of screen flickering was sampled every 10 seconds and 500 samples in total were obtained for checking the frequency distributions statistically.

F. Computational cost in smartphones

To evaluate the computational costs of the stimulation App when running on a smartphone the processing time required for generating the stimulation, power consumption, and memory usage were measured. This was done for both active and sham modes of both audio and visual stimulation.

1) Processing time for stimuli generation: The time required between the user clicking the start button and the stimulation being started was measured by a Timer Object. For each mode, the processing time was measured 100 times, and the average values were given as the result. This measurement therefore gives the latency for setting up a new stimulation.

2) Memory usage: The smartphone App memory usage was inspected in real-time via the Android Studio Profiler while the App was running. 10 data points were sampled for each mode and the mean values were calculated. This measurement will indicate whether the App is memory intensive, which might affect the ability to run other Apps simultaneously.

3) Power consumption: Power consumption during App execution was measured by using Battery Historian, a dedicated tool for inspecting the battery usage on Android smartphones [20]. For each stimulation mode, 3 measures were performed when other background services were turned off, each with a duration of 10 minutes, and the mean power consumption is reported. Note that the visual mode was measured under normal indoor light intensity, the absolute value of power consumption will vary depending on the screen brightness level chosen by the user. For the BB stimulation, the volume was set to half of the maximum.

III. Results

A. Stimulation characterization

Fig. 2 shows the power spectra of the audio signal measured via the data acquisition system. The active stimulation mode (Fig. 2.A) constantly outputs a 400 Hz tone for the left ear and a 410 Hz tone for the right ear, which can accurately produce a 10 Hz BB. The sham mode (Fig. 2.B) outputs

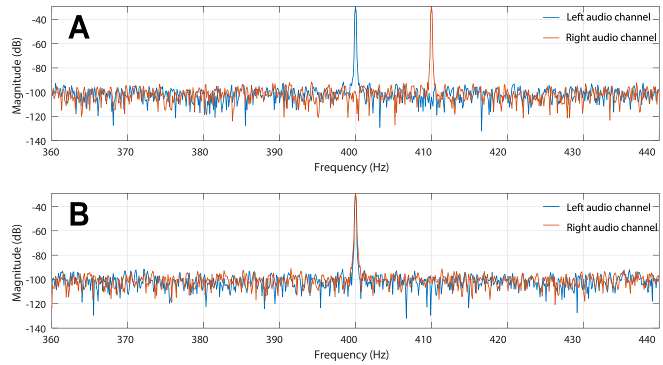

Fig. 2. Analogue signal test of the stereo audio channels in the frequency domain for the acoustic stimulation. (A) 10 Hz stimulation; (B) Sham stimulation.

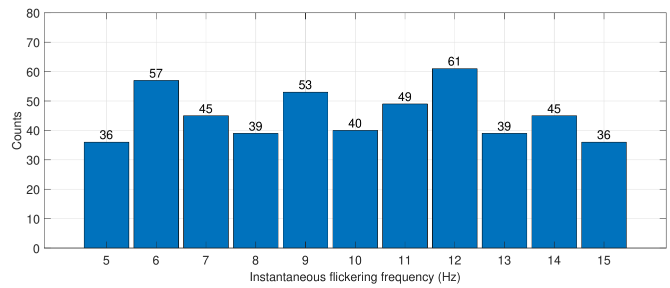

Fig. 3. Histogram of the screen flickering frequencies in the non-rhythmic sham visual stimuli.

400 Hz and 400.01 Hz, generating a near monotone outside the normal EEG frequency range.

For visual stimulation, the active mode constantly outputs the visual stimuli at 10 Hz as expected. In the sham mode, Fig. 3 shows the histogram of the instantaneous frequencies of the screen flickering in the range 5 to 15 Hz. The probability of each frequency value occurring is approximately uniformly distributed. The randomization of frequency change produces the of non-rhythmic stimuli as desired.

B. Computational cost in smartphones

The computational costs for running our stimulation approach on a smartphone are shown in Table II. The time required for generating the audio and visual stimulation is very similar, at around 80 ms. Here, the computational time consists of a new Android activity launching, setting up the widgets required in this activity, and calling the methods to generate the stimulation.

For an open-loop stimulation, which has fixed parameters

TABLE II
COMPUTATIONAL COSTS OF GENERATING BRAIN STIMULATION IN SMARTPHONES

	Audio		Visual	
	Active	Sham	Active	Sham
Computational time (ms)	82.5	89.1	81.4	78.9
Memory usage (MB)	93.6	94.9	136.2	148.3
Power consumption (mAh/h)	346.3	287.1	349.6	175.1

for generating the specific stimuli, as is our current aim, 80 ms processing time is very fast and largely imperceptible when starting a new stimulation session. It also provides a good starting point for creating *closed-loop* stimulation protocols where the stimulation parameters are changed in real-time based upon currently sensed data (whether from the EEG or other devices in a Body Sensor Network). For example, for the computer-based closed-loop brain stimulation platform reported in [21], the total computational time required for data acquisition, processing and stimulation is around 70 ± 5 ms. Our smartphone-based platform takes slightly longer due to less powerful chipsets, and so further optimization will be required to enable closed-loop use.

Memory usage for visual stimulation occupies 136.2 MB for stimulation and 148.3 MB for sham mode, which is higher than the audio mode at 93.6 and 94.9 MB. This is due to the usage of the screen in visual mode. Nevertheless all modes consume low memory during the execution for a GB level memory smartphones.

The power consumption required for our App is between 175.1 and 349.6 mAh per hour, where the visual sham mode consumes the lowest power and other modes consume more, at around 300 mAh per hour. Note that modern smartphones normally have a battery capacity between 3000 and 5000 mAh, which indicates that the App can be used continuously for more than 10 hours. There is a substantial difference in power consumption between the active and sham modes, which could provide a route for unblinding by motivated users. In future versions it may be beneficial to add dummy routines to equalize the resources used in both cases.

IV. Conclusions

This paper presented an Android App for portable sound/visual neurostimulation, which also contains sham stimulation modes allowing active and placebo studies to be performed. Accurate active and sham stimulation was demonstrated for sound and visual modes via hardware tests. The low computational costs required for generating the stimulation indicates its potential for long-term use, and use in future closed-loop stimulation App developments. This App could be beneficial for future at-home use of neurostimulation, and the integration of actuation into body sensor network deployments.

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