A low-cost MRI compatible keyboard

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ABSTRACT

Neuroimaging is a powerful tool to explore how and why humans engage in music. Magnetic resonance imaging (MRI) has allowed us to identify brain networks and regions implicated in a range of cognitive tasks including music perception and performance. However, MRI-scanners are noisy and cramped, presenting a challenging environment for playing an instrument. Here, we present an MRI-compatible polyphonic keyboard with a materials cost of 850 $, designed and tested for safe use in 3T (three Tesla) MRI-scanners. We describe design considerations, and prior work in the field. In addition, we provide recommendations for future designs and comment on the possibility of using the keyboard in magnetoencephalography (MEG) systems. Preliminary results indicate a comfortable playing experience with no disturbance of the imaging process.

Author Keywords

Neuroimaging, input device, MRI-compatible, fMRI, MEG, keyboard, optical sensing.

ACM Classification

Human-centered computing~Interface design prototyping
Hardware~Sensor devices and platforms

1. INTRODUCTION

Functional Magnetic resonance imaging (fMRI) is a common methodology for studying music performance. Active neurons require glucose to return to their original state, a process which causes blood to release oxygen at a higher rate compared to inactive neurons. In blood-oxygen-level dependant (BOLD) fMRI this is recorded as an increased signal [10]. Coupled with the high spatial resolution of MRI this allows identification of which brain regions are active in a given cognitive task compared to another task with an accuracy of 1-2 mm. In contrast to other human brain research techniques such as electroencephalography, fMRI allows for better identification of both cortical and subcortical activity.

The study of how music perception and performance affect brain function and structure has recently established itself as an important and burgeoning topic within cognitive neuroscience [12]. A challenge for fMRI investigations into music making is to create MR-compatible instrument-like interfaces. In order to analyse and judge a musical performance, and provide an ecologically valid setting, researchers need to be able to accurately capture behavioural data. The MRI-scanner presents a challenging environment for user interfaces, due to the strong magnetic fields, the limited space, and the need for participants to keep their head as still as possible to avoid motion artefacts. Previous studies have limited themselves to for instance imaginary playing or non-functioning instruments [3, 7, 9]. Imagined playing paradigms, however, are not optimal since they do not supply feedback for objectively verifying that participants are, in fact, imagining playing. Using non-functioning instruments is a step forward, but does not provide participants with the full experience of music performance due to lacking auditory feedback. Because of these constraints, drawing conclusions on brain activity without a solid behavioural fundament might lead to suboptimal results, which highlights the need for MRI-compatible instrument-like interfaces.

In this paper, we first present an overview of the challenges and the recent development in designing fMRI-compatible musical interfaces, followed by a description of the design and prototyping process of our MRI-compatible polyphonic keyboard. The device presented is a fully functioning keyboard, currently in use in our 3T MRI-scanners. Due to its design, it is with minimal alterations compatible with MEG systems. We discuss knowledge gained in the process, preliminary user experience findings from an ongoing MRI-study into musical improvisation and conclude with providing recommendations for future designs.

2. DESIGN CONCERNS

The MRI scanner presents an environment that is challenging for conventional digital music instrument (DMI) design. Without going into the specific physics, an MRI scanner uses a powerful static magnetic field, radio waves and field gradients to record signals that are used to generate brain images. This reduces the possible choice of materials, since the static magnetic field is sufficiently powerful to be able to pull ferromagnetic objects from meters away into the bore of the scanner, often with immense acceleration. As this is where the head of a subject is placed in cognitive fMRI studies, such materials are strictly prohibited within the scanner room. Even non-ferrous metallic

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objects might prove challenging to use, due to induction of electrical currents from the time-varying magnetic fields resulting in distorted images [11].

While MRI-safety is a matter of choosing the correct materials, MRI-compliance demands that the designs do not cause any image artefacts and retains normal function during the operation of the scanner. A commercially available MRI-compatible MIDI keyboard (Hybridmojo LLC) containing non-ferrous electronics were tested before embarking on this project. However, while the keyboard turned out to be safe for MRI-use, the 3T MRI-scanner used interfered with its circuits - making the keyboard play itself during scanning. This highlights the challenges in using electronics within the MRI environment. We therefore designed our keyboard using only plastic and fiber-optics materials.

In addition to these concerns, it should be kept in mind that an MRI-scanner is for many participants an uncomfortable experience. The most common wide-bore MRI systems generally have a bore with a diameter of 60-70 cm, with our system measuring in at 60 cm (Siemens MAGNETOM Trio 3T). The participants head is fixated within a head coil, providing little leeway for movement. During fMRI sequences, acoustic noise from the scanner will easily reach 120 dB SPL [4], and common experiment paradigms often necessitates 30-40 minutes of scanning time. It is thus important to take the participants comfort into account when designing DMIs for use in MR-scanners.

2.1 Recent development in MRI-compatible musical interfaces

Various MRI-compatible sensors exist, which are suitable for designing musical instruments and interfaces. However, the use of electronic circuits demands extensive testing to ensure the imaging processing is not disturbed, and what might work in a 1.5T scanner does not necessarily work in a 3T or 7T scanner. For this reason, optical sensing is preferable, as it does not affect image acquisition. There exists various fiber-optic click-button interfaces, which can be used to trigger sounds. These devices generally use the USB protocol to emulate keypresses on a connected computer, resulting in too high latency for musical performance.

Recently, there has been an increasing interest in designing and using MRI-compatible musical interfaces, exemplified for instance in the optoacoustic cello presented by Hollinger and Wanderley in [6]. Concerning MRI-compatible keyboards, we are aware of a few other attempts: Hollinger et. al. as described in [5], a specially designed keyboard by Mag Design and Engineering (Sunnyvale, CA) as described in [2, 8], and a commercially available keyboard from Hybridmojo[2]. However, the commercially available keyboard did not function properly in our 3T MRI-scanner, and the others are one-off designs. Our device is a natural continuation of the piano described in Hollinger et. al. with the goal of presenting a functional, low-cost polyphonic MR-compatible device offering a naturalistic setting for the participants.

3. DESIGN

3.1 Physical design

Apart from fulfilling the criteria for an MRI-safe and compatible device, we decided on making a slim design for low weight and a size that would be comfortable for prolonged use while resting on the participants lap. We used 25 full size keys, covering two full octaves. This size allowed an average sized participant with the keyboard resting on their legs to reach all keys by moving the forearm only, with their elbow resting on a pillow. As motion artefacts are a challenge in MR-studies, this was an important part of the design. The keys were taken from an Edirol MIDI keyboard, and stripped for all metal parts. In order to house the keys a minimalistic laser cut layered design in acryl was produced on a KERN HSE100 laser system[3]. A total of 12 layers were then assembled, with 3D printed holders for the fiber-optic cables. This design allows for easy dis-/reassembly of the devices in case of repairs or alterations. The completed keyboard can be seen in figure 1.

Figure 1. The MRI-compatible keyboard, with fiber-optic cables exiting at the back of the laser cut case.

3.2 Sensing

We used 660nm LEDs with the Versatile Link fiber-optic system from Avago technologies[4], with each key having its own transmitter and receiver circuit placed outside the scanner room. The light is guided through fiber-optic wires from the transmitter and back to the receiver. Inside the keyboard there is a gap between the fibers where the key can break light transmission, allowing us to detect changes in key status. This way, only the plastic optical cables and the keyboard itself are inside the MR-room, ensuring no interference between the scanner and the keyboard.

In order to keep a simple design, we decided to only capture key press and release, omitting velocity. It would be possible to implement velocity by measuring the continuous change of light transmission prior to the key being fully depressed. However, this would complicate the microcontroller code and require extensive calibration. Another solution, which we are considering for an updated design, is a double-tap design wherein the key breaks light transmission twice in rapid succession. Such an implementation would alleviate the calibration issues of measuring continuous change, and present a solid measurement of key acceleration. While the lack of velocity impacts the sensation of playing a real instrument, it should be remembered that the dynamic range available for the player in the noisy MR-environment is severely limited.

3.3 Hardware and firmware implementation

For each of the 25 keys there is an output from the receiver circuit that needs to be monitored, and interpreted into a MIDI signal. In order to reduce the amount of input pins needed on the microcontroller we used 4 daisy-chained Texas Instrument SN74HC165 8-bit parallel-load shift-registers. This configuration allows for reducing a total of 32 inputs to only 4 serial outputs. Our current keyboard uses only 25 inputs, but this design would allow for augmenting the keyboard with further controls, such as pitch-bend, modulation, or a sustain pedal. The 4 serial outputs are then connected to an Arduino Nano, running an ATmega328 microcontroller at 16 MHz with a serial data transmission rate of 31250 bps. The setup is shown in figure 2.

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[2] Hybridmojo LLC, http://www.hybridmojo.com/

[3] KERN HSE100, http://www.kernlasers.com/

[4] Now known as Broadcom Limited, http://www.broadcom.com/

The Arduino firmware was written using the Arduino IDE 1.8.1[5]. It functions as a simple state machine, where each key is either in a ON or OFF state. It constantly polls the input pins, and if any change is detected it sends out either a note-ON or note-OFF message depending on the previous state of the specific key, thus ensuring full polyphony. MIDI messages are handled using the Arduino MIDI Library v4.3.1.[6], transmitting these through a serial output port using a MIDI-specification 5-pin DIN connector [1].

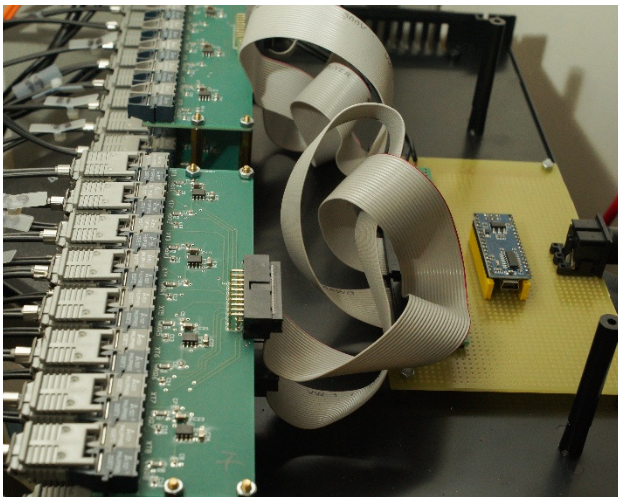

Figure 2. The fiber-optic connectors, with the Arduino microcontroller and MIDI connector shown to the right.

4. TESTING AND RESULTS

We have tested the keyboard on 22 participants, for a total of 8 hours and 48 minutes of actual playing. The participants played an average of 24 minutes each. They were instructed to perform the melody of a well-known jazz standard, to sight-read a new melody, improvise melodically, and to improvise freely. In figure 3 an example of how participants and the keyboard were positioned inside the scanner is shown. Figure 4 shows a sagittal, coronal and axial view of raw data from one participant. The topmost images show the average of the BOLD-sequence, taken when the participant is playing, while the bottommost shows the result of a diffusion tensor imaging sequence, taken with the keyboard placed in the vicinity of the scanner. No adverse effects on imaging were found, nor have we received any complaints of discomfort with the physical placement of the keyboard. An occasional challenge is self-triggering and multi-triggering of some keys. This self-triggering happens due to the fiber-optic cables being moved around, and is usually solved by refastening the cables. We intend to fix this problem by better cable management in an updated version of the keyboard. Multi-triggering happens when the user continuously holds the key at a specific point, causing the optic signal to hover around threshold range. This problem could be fixed with implementing a gate on incoming triggers, set at a rate which is just below the fastest retriggering time. However, in the currently running study we found that instructing participants to fully depress keys solved the issue.

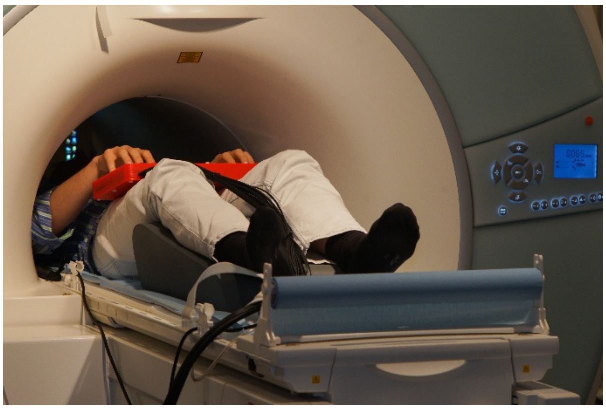

Figure 3. Example positioning of a participant and the keyboard inside the scanner.

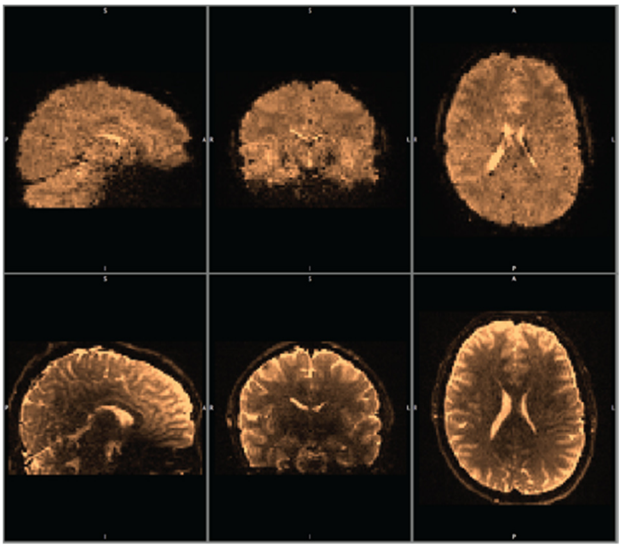

Figure 4. Sagittal, coronal and axial view of BOLD and DTI raw data.

For the currently running study the keyboard is attached by a MIDI-cable to a Roland JV-1010 hardware synthesizer for generating audio. From the synthesizer, we use the MIDI-thru functionality to record the MIDI data using an external sound card on a Windows computer running PsychoPy [10]. This way we avoid any extra latency from using a software synthesizer. The piano sound from the synthesizer is mixed with a backing track, delivered through OptoACTIVE active noise cancelling headphones from Optoacoustics[7]. This solution ensures that latency is minimal, while providing the participants with an adequate signal-to-noise ratio.

4.1 Challenges and recommendations

In our currently running study, the keyboard is placed on the participants lap, with their legs on a pillow. This puts the keyboard at a small angle, making it easier to reach with only their right hand. However, this position could be a challenge for persons with a larger girth. A possible solution here would be to fasten the keyboard on a tilted stand, and adjusting the playing height for each participant. This might pose a challenge due to the bore size of the MRI-scanner, but would allow for more controlled positioning of the keyboard.

It is worth noting that the key action of our keyboard is more similar to that found on a Hammond organ, than on a piano, with the keys

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[5] Arduino Foundation, http://www.arduino.org/

[6] Arduino MIDI library, http:/www.fortyseveneffects.com/

[7] Optoacoustics Ltd., http://www.optoacoustics.com

resting on the base of the laser cut case in their fully depressed state. Since participants in our study were used to playing on synthesizers and MIDI-controllers, this did not pose a problem. It should however, be kept in mind when recruiting participants that solely play on acoustic pianos such as is usually the case for most classically trained pianists.

While the laser cut base provided an elegant solution to creating a low-weight frame for the keyboard, the 3D printed cable holders exhibited a size mismatch due to a lacklustre printer calibration and material shrink. We were able to work around this issue by manually adjusting the parts post-print. For future designs, it is worth considering allowing for manual adjustment of both the laser cut and 3D printed parts, by having excess material and sanding it afterwards.

4.2 MEG compatibility

It should also be possible to use our keyboard with MEG. MEG is a functional neuroimaging technique, which records the magnetic fields created by the naturally occurring electrical currents in the brain using highly sensitive magnetometers. As these fields are smaller than the ambient magnetic noise MEG systems are placed in magnetically shielded rooms. Participants position their head in a headrest, either in a supine position, or sitting in a chair. The system is quiet, and does not have the same physical restrictions as the MRI environment. However, in order to avoid any noise in the recordings a complete plastic and fiber-optic design is preferred for MEG-compatible devices. Our keyboard fulfils this criterion, and should be suitable for use in the MEG. We intend to test this in upcoming studies. As motion artifacts can be a concern in MEG studies, we would recommend creating a keyboard stand in order to better control arm motion in participants.

5. CONCLUSION

In this paper, we have presented a viable MEG and MRI compatible keyboard. The keyboard costs around 850 $ in materials, factoring in an estimated 70 $ for the 25 keys, which is relatively low-cost for most labs with neuroimaging facilities. While it is not of comparable quality to the keyboards one will find in homes, studios and on the stage, it serves its purpose well. The approach of using only fiber-optics and plastic is in our opinion the best strategy to future-proof any MRI compatible instrument, with both 7T scanners and MEG becoming increasingly common in neuroscience.

We would encourage the design of novel MRI-compatible DMIs. For instance, in order to investigate how learning to play a musical instrument changes networks in the brain, an instrument that is playable both inside and outside of an MRI-scanner would provide a more ecological valid study. Another aspect is the neural correlates of error-correction, for example in non-linear instruments. We hope that further studies into how the brain behaves when playing an instrument will synergistically benefit both the design of interfaces for musical expression and the neuroscience of music.

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