Music and the Brain – Design of an MEG Compatible Piano*

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Abstract— **Magnetoencephalography (MEG) neuroimaging has been used to study subjects' responses when listening to music, but research into the effects of playing music has been limited by the lack of MEG compatible instruments that can operate in a magnetically shielded environment without creating electromagnetic interference. This paper describes the design and preliminary testing of an MEG compatible piano keyboard with 25 full size keys that employs a novel 3-state optical encoder design and electronics to provide realistic velocity-controlled volume modulation. This instrument will allow researchers to study musical performance on a finer timescale than fMRI and enable a range of MEG studies.**

I. Introduction

Studying neurological activity while listening to and playing music promises insights into cognitive function, the auditory and motor cortexes, and even music therapy for conditions, such as autism [1]–[3]. Functional magnetic resonance neuroimaging (fMRI) has been employed in music-brain interaction studies that investigated the effects of learning to read and play music [4], passively listening to music [5], fingering a mute keyboard [5], [6], and playing an MRI-compatible instrument with real-time auditory feedback [7]–[9].

Magnetoencephalography (MEG) neuroimaging measures the brain's magnetic fields directly using hundreds of cryogenically cooled SQUIDs (super conducting quantum interference devices) located in a helmet. MEG provides a temporal resolution on the order of milliseconds, the time scale at which neurons communicate, unlike the several second timescale of the hemodynamic response measured by fMRI [10]. Compared to electroencephalography (EEG) "caps," MEG provides greater spatial resolution, each sensor is independent (no reference ground or averaging), and is less susceptible to muscle interference [11], [12].

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Because the brain's magnetic signals are a billion times weaker than the Earth's magnetic field, MEGs are installed inside shielded enclosures, any metal must be completely stationary, and any movement of the subject must be limited while the head is constrained rigidly inside the helmet [13]. Due to the strict interference restrictions, musical MEG studies have been limited primarily to passive listening.

Several instruments that provide real time auditory feedback have been described for use with fMRI including: a Ballagumi, a flexible silicone interface embedded with fiber optic sensors [14]; a gut string cello [15]; and an instrumented section of salvaged piano keyboard [16]. The Ballagumi's unfamiliar interface limits its use and the cello requires specialized skill to play, is large and involves head and shoulder motion. Only [16] describes the design of a multi-tonal instrument compatible with the constraints of an MEG, however, is not explicitly MEG-compatible, the authors reported unreliable signals, and the device required re-calibration before each use. An instrument consisting of a single piezo button, which provided for limited musical expression, was described for MEG use [17].

The goal of this project was to develop an instrument with a familiar interface that would enable amateurs and professionals alike to play common songs ("Happy Birthday" was used as a benchmark) during MEG imaging, without causing interference. Sumitomo Heavy Industries, Ltd. (SHI) Engineering Physics Dept. proposed this research tool's development for use with the new MEG machine they are designing. The MIT MEG Lab provided hands-on technical assistance. Together, we seek to help expand understating of the capabilities and applications of MEG technology.

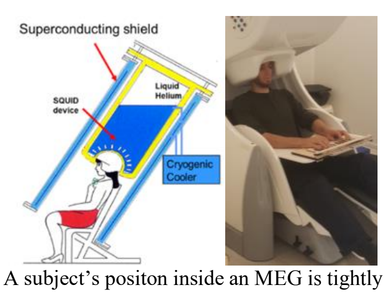


Figure 1. A subject's positon inside an MEG is tightly constrained.

II. Design Approach

A. Functional Requirements

From discussions with SHI and in reviewing prior art the following requirements were identified to guide the design:

- Compatibility: Neither the device itself nor its use may distort the MEG signal.
- Familiarity: The interface should look and feel like a commonly played instrument and allow control over the pitch, intensity, and timing of notes.
- Music: Subjects must be able to play at least eight distinct notes as well as chords of more than 3 simultaneous notes, with a latency between key press and audio output outside the range of human perception (under 25 ms).
- Output: The device must output timing signals and record notes for correlation with MEG imaging.
- Size: The device must fit under the magnetic shield of SHI's prototype MEG and be readily accessible by the subject.

B. *System Architecture*

A range of possible instruments were reviewed and a standard piano format was chosen for its familiarity, low barrier to playing, and concentration of movement in the hands, thus limiting the potential for muscle and other movement artifacts. The final prototype system, fabricated at MIT, is shown in Fig. 2. The piano consists of a non-metallic keyboard with 25 full-sized keys (two full octaves), sufficient for a variety of two-handed musical pieces. Each key is monitored by a three state linear encoder that is connected by a pair of optical fibers to an LED and a photodiode. These, components, along with sensing electronics, are located outside the shielded enclosure. The encoder signals provide information on both key identity and speed of key press, which determines note intensity. A microcontroller converts this information into notes and amplitudes in the MIDI format and a synthesizer outputs the resulting music to the MEG enclosure's speakers. The following section describes the design of these components in more detail.

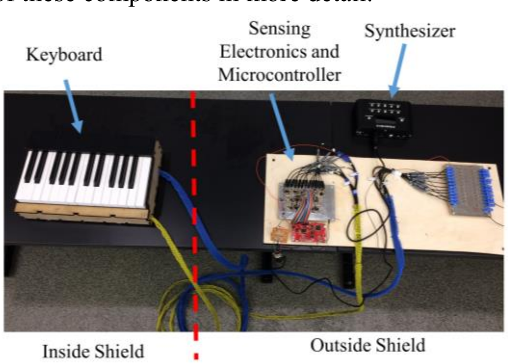


Figure 2. The device consists of a 25 key piano keyboard inside the magnetic shield, connected fiber-optically to the electronics that register key presses and produce sound

III. Detailed Design

A. *Packaging & Key Mechanics*

To preserve the dimensions and texture of a familiar piano keyboard, the design incorporated replacement keys for a YAMAHA electric keyboard (K64UC Style 64U). For key return, ULTEM polymer springs were chosen to approximate a 60g touchweight (measured at note onset). Fig. 3 shows the encoder block assembly. The encoders are adhered to replaceable clips that are press-fit into existing features on the keys. Transmitting and receiving fiber pairs are held in axial alignment under each key by modified mating sleeves (IF CS2, i-fiberoptics.com), which are threaded into an encoder block. Alignment features on the encoder block maintain appropriate key spacing, and a narrow slit ensures the encoder is perpendicular to the fiber ends. Mechanical stops built into the encoder block limit the key, and thus finger, travel to 1 cm.

The prototype packaging consists of an acrylic and wood enclosure fastened to the internal frame by nylon machine screws. The internal structures are positioned on a base plate by plastic locating pins to preserve alignment after re-assembly. The packaging accommodates a 30 mm fiber bend radius to minimize signal attenuation. For the purposes of testing and demonstration, the electronics were mounted exposed on a plywood board with adequate strain relief, but will be enclosed once fully debugged. Versatile link fiber optic connections allow the 5m fibers to be temporarily disconnected and routed out of a magnetically shielded room so the system can be stored or used among several MEG or fMRI systems.

B. *Signal Encoding*

Each key press is communicated to the sensing electronics by an encoded optical signal. Durable plastic optical fibers were selected to eliminate the risk of the connecting wires functioning as antennas and carrying interference into the shielded enclosure. Two modes of optical detecting were considered: reflective, which measures the intensity of returned light along a fiber impinging upon a reflector, and transmissive, which interrupts the signal between two fibers. The former requires precise reflector alignment and attempts to mitigate this sensitivity with a diffuse reflector result in low signal strength. Transmissive sensing through an encoder was selected for its ability to produce a strong signal and its high tolerance to key misalignment. When a key is hit, it is necessary to know its speed and whether it is moving up or down. Direction sensing in an encoder is often achieved through quadrature, which would require doubling the number of optical fibers, but instead, we developed a novel three-state linear encoder, uniquely tailored to identifying key hits. The three-state linear encoder is depicted in Fig. 3 and Fig. 4.

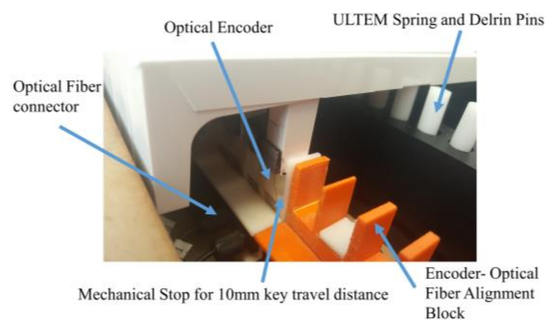


Figure 3. The three-state encoder strip mounts to the key and slides into the encoder alignment block, interrupting transmitting fiber optic cables. ULTEM polymer springs return the keys upward.

The linear encoder's strip consists of three bands of different opacities printed on standard transparency film. As depicted in Fig. 4, a key is pressed, the strip passes down through a slot between two optical fibers and reads, in order, transparent, fully opaque and semi opaque. A downward press is identified by the first edge transition from clear to opaque, the time it takes the opaque band to pass indicates speed, so after the second edge transition from opaque to semi-opaque the note is fully specified. This mimics a real piano's hammer release just before the key bottoms out.

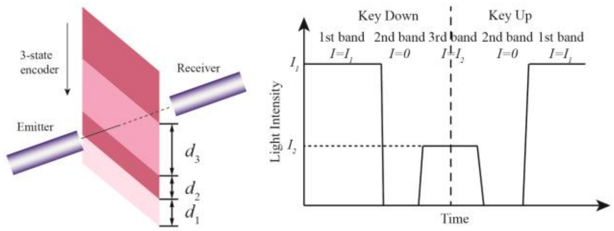


Figure 4. Bands of three opacities *(top)* interrupt the transmitted optical signal to produce a signal that changes over the course of a key press *(bottom)*.

C. Sensing Electronics

The circuits shown in Fig. 5 convert light intensity into voltage signals and determine key state and press velocity. A transmitting LED (IF E97, i-fiberoptics.com) outputs a constant signal at 660 nm, a wavelength selected to minimize attenuation in the plastic optical fiber. A phototransistor (IF D92, i-fiberoptics.com) receives the encoded signal and a transimpedance amplifier (LM6132, digikey.com) outputs an analog voltage, V_{out}, which follows the light intensity signal, determined by

$$V_{out} = \frac{i}{R_f} \quad (1)$$

Two comparators (TLV3702, digikey.com) throw digital pins on the processor high or low depending on key state (Fig. 5). The processor uses these signals to interpret key state.

Processing

With the requirement to play chords, the processing system must accommodate multiple comparator signals changing simultaneously. Continuously polling in a main loop would miss one of two simultaneous events; by contrast, hardware interrupts force each event to be serviced.

An MSP432 microcontroller (Texas Instruments) accommodates the 25 hardware interrupts and 25 digital inputs needed to play multiple simultaneous notes without error. The hardware interrupt, reading from comparator A, handles velocity sensing; the main polling loop checks whether the key is up or down, reading from comparator B.

Table 1, describes the high-level logic of the processing system during a normal key press (for a detailed logic diagram, see the Appendix).

As the edges shown in Fig. 5 trigger the interrupts, the system gathers a time interval to determine velocity and sends a MIDI signal to play a note at the corresponding volume. Ignoring rising edges after edge 3 passes, while relying on the main loop to silence any note still playing if the corresponding key is up, ensures that a note will not stop or replay until the key is raised.

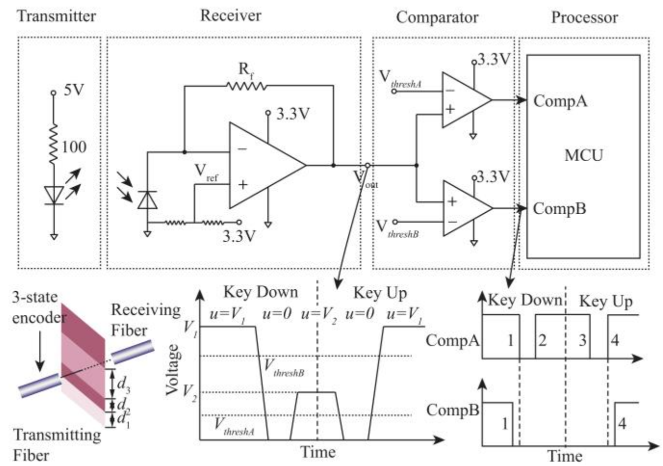


Figure 5. From left to right, the intensity differences from the key encoder are converted to an analog voltage signal, which is compared against threshold voltages to produce digital signals that communicate key state to the processor. The threshold voltage for comparator A is set to be lower than V_1 (maximum intensity), while the threshold voltage for B is set to be lower than V_2 (half intensity) and higher than V_1. If A is high and B is low, the key is down; if A and B are high, the key is up.

TABLE 1. PROCESSING LOGIC

Event	State Values			Instructions
	Comp A	***Comp B***	***Currently Sending Note?***	
Edge 1	Low	Low	No	Get t_1
Edge 2	High	Low	No	Get t_2, calculate Δt, MIDI note on
Edge 3	Low	Low	Yes	Continue playing note, Ignore rising edges
Edge 4	Rising edges ignored			Does not trigger
Main Loop		High	Yes	MIDI note off

The MIDI signal from the processing unit is passed via buffered UART communication hardware to the MIDI synthesizer, which applies onset and attenuation characteristics to make the audio slowly decay when sustained, similarly to that of a real piano. A digital trigger signal of is fed to the data acquisition unit of the MEG via a BNC connector to allow synchronization between sound generation and brain signals.

IV. TESTING

The first test was conducted on the bench to verify that the signal chain met the <25 ms lag specification; with 25 signals and three possible states each, computation time was a concern. An oscilloscope was used to measure the time delay between the comparator signal that triggers a note and the output from the synthesizer's audio jack. This was delay was 5 ms; less than the 15 ms delay due to the 5 m distance that sound must travel at 343 m/s from the speakers to the subject. A more thorough sensitivity analysis will be conducted before commissioning the device.

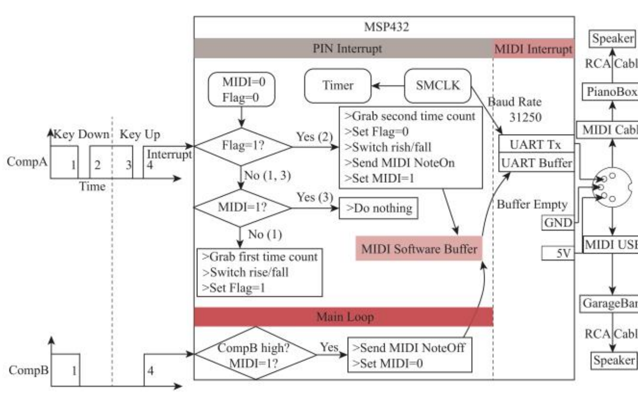
To evaluate interference caused by muscle activation, preliminary testing was conducted in MIT's MEG lab while the design was being developed. With the MEG recording, a team member seated inside the enclosure, but outside the MEG, made "key tapping" motions at varying distance from lap to head position and qualitative results suggested a lack of consistent interference unless the hands were proximal to the sensor helmet. Further work will establish guidelines for the extent of allowable movement, and we have received MIT IRB approval to execute a formal test procedure. A team member will be seated quietly next to the MEG (with no brain in the helmet) and the piano placed on the tray table. After acquiring a baseline for MEG signals, the tester will play single notes, chromatic scales and progressive chords, each requiring increasing motion, and piano-dome distance will also be varied. The notes will be recorded and the MEG data examined in narrow windows around the muscular events, by analyzing segments of data time-locked to the 5V trigger signals.

In the course of this testing, we will look for evidence of detection errors, especially when being played at high speed, and validate the data collection and triggering protocols. The cables will be disconnected and reconnected and then together with the circuitry subjected to movement and vibrations. Once the electronics and code are validated and we are satisfied that the device can reliably survive disassembly, transportation, and reassembly it will be commissioned for research.

V. Conclusion

This device will offer researchers a flexible tool to investigate brain-music interaction at a fine temporal resolution. The piano form and realistic feel will enable a wide range of studies, from examining the real-time formation of neural responses and cognitive networks as subjects memorize a new tune, to comparing the response of non-musicians to musicians when an unexpected dissonant note is introduced, to searching for more salient markers of ASD and other similar disorders. In addition to being useful to basic research, an MEG compatible keyboard may find clinical relevance in investigating the mechanism and optimizing existing applications of music therapies.

Appendix



This diagram outlines the processor logic flow in more detail. "Flag" and "MIDI" are state variables; "Flag" stores whether the interrupt is expecting a rising or a falling edge. "MIDI" stores whether a MIDI note is playing (MIDI NoteOn sent) or is off (MIDI NoteOff sent, after MIDI NoteOn). A timer module is run in background for velocity sensing. "Switch rise/fall" switches the interrupt type so that it services only either rising or falling edges.

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