

# Haptic fMRI : Reliability and Performance of Electromagnetic Haptic Interfaces For Motion and Force Neuroimaging Experiments

Samir Menon<sup>1</sup>, Jack Zhu<sup>1</sup>, Deeksha Goyal<sup>1</sup>, and Oussama Khatib<sup>1</sup>

**Abstract**—Haptic interfaces compatible with functional magnetic resonance imaging (Haptic fMRI) promise to enable rich motor neuroscience experiments that study how humans perform complex manipulation tasks. Here, we present a large-scale study (176 scans runs, 33 scan sessions) that characterizes the reliability and performance of one such electromagnetically actuated device, Haptic fMRI Interface 3 (HFI-3). We outline engineering advances that ensured HFI-3 did not interfere with fMRI measurements. Observed fMRI temporal noise levels with HFI-3 operating were at the fMRI baseline (0.8% noise to signal). We also present results from HFI-3 experiments demonstrating that high resolution fMRI can be used to study spatio-temporal patterns of fMRI blood oxygenation dependent (BOLD) activation. These experiments include motor planning, goal-directed reaching, and visually-guided force control. Observed fMRI responses are consistent with existing literature, which supports Haptic fMRI’s effectiveness at studying the brain’s motor regions.

## I. INTRODUCTION

Haptic fMRI Interfaces [1], [2], [3], [4], [5], [6], [7], [8], [9], [10] offer the ability to conduct neuroimaging experiments for a variety of day-to-day motor tasks in virtual environments [11], [12], [13], [14] and are an increasingly popular tool to study the brain. A critical advantage is the ability to precisely monitor motions and apply forces when required. Wider adoption, however, requires demonstrating that multi-axis haptic interfaces can provide high-resolution fMRI measurements (mm, sec) [15], [16] reliably over the long term. A study of how such devices operate over the long term is thus a limiting factor.

Research efforts have led to numerous haptic interfaces for fMRI. These rely on a variety of actuators such as electro-active polymers [17], pneumatics [1], and hydraulics [18], [19]. Cables, with dynamic models to improve performance [20], are also promising. Functional interfaces include a shielded PHANTOM [5], [21], a wrist device [10], a pneumatic device [1], and a family of electromagnetically actuated devices [7], [9]. Present efforts are directed towards devices with more degrees-of-freedom, or towards achieving high-fidelity force control, natural motions [22] and uniform inertial properties across a large three-dimensional workspace. We believe, in addition, that technological ad-

\*This work was supported by BioX, Stanford University, the Stanford Neurosciences Institute, and the Center for Cognitive and Neurobiological Imaging, Stanford University.

<sup>1</sup>S. Menon, J. Zhu, D. Goyal, and O. Khatib are with the Stanford Robotics Laboratory, Department of Computer Science, Stanford University, Stanford, CA 94305, USA [smenon@cs.stanford.edu](mailto:smenon@cs.stanford.edu), [jackzhu@stanford.edu](mailto:jackzhu@stanford.edu), [deeksha@stanford.edu](mailto:deeksha@stanford.edu), [ok@cs.stanford.edu](mailto:ok@cs.stanford.edu)

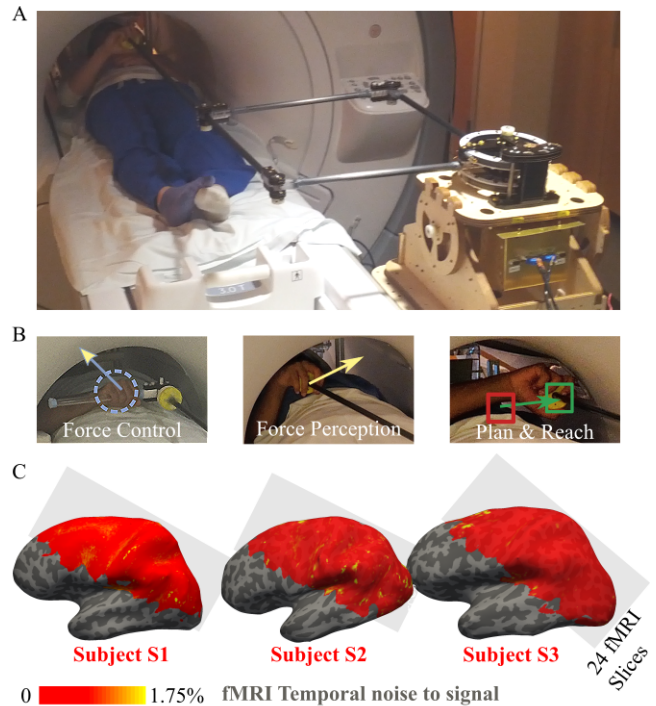


Fig. 1. Haptic fMRI Experiments. (A) Haptic fMRI Interface 3 (HFI-3), one of a family of electromagnetically actuated fMRI-compatible haptic interfaces. (B) A variety of motor neuroimaging experiments conducted with HFI-3. Left to right: active force control of a lever with visual feedback provided to the subject; passive force perception where a subject holds a position and experiences a perturbative force; and a plan and reach experiment where subjects make three-dimensional reaches to random locations. (C) fMRI temporal noise measurements plotted on inflated brain models for three subjects who performed the experiments (fMRI baseline = 0.8%). The actual fMRI scan volume is indicated with gray boxes.

vances have matured to a point where long-term reliability and performance studies are very desirable.

Here, we present a long-term study of Haptic fMRI Interface 3 (HFI-3; Fig. 1.A) [7], [23], [24], [9], an electromagnetically actuated fMRI-compatible haptic interface, and demonstrate how to obtain high fidelity fMRI measurements for a variety of different motor neuroimaging experiments (see Fig. 1). We show how electromagnetic actuation affects fMRI by outlining improvements in noise due to the addition of motor shields (Faraday cages), capacitive electrical connection filters, fieldmaps, and regular scanner recalibration. Our analysis is spread over one hundred and seventy-six scan runs (6-10 mins each) distributed over thirty-three scan sessions (multiple days). The results demonstrate noiseless operation for HFI-3 for experiments involving either move-

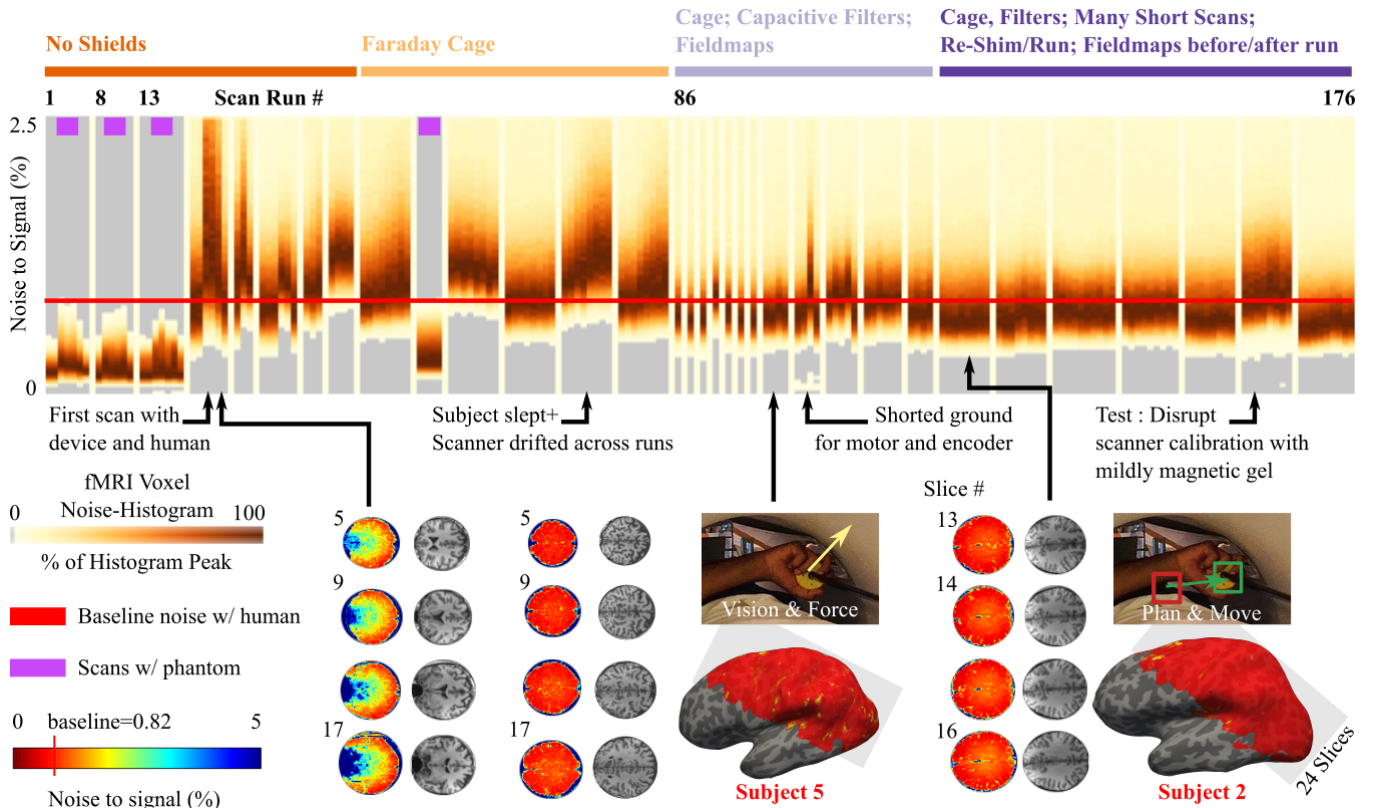


Fig. 2. HFI-3 Temporal Noise Characteristics. (Top) A heatmap of temporal noise histograms measured during one hundred and seventy-six fMRI scans during HFI-3’s development. Each column in the heatmap is a histogram of the noise distribution obtained from an fMRI volume over the duration of a single scan session (6-10min). A block of columns indicates a set of scans that were conducted on the same day. Darker areas indicate more voxels had a given noise-to-signal value. The red line is baseline noise for a sleeping subject. Observed reductions in noise with increasing scan id demonstrate the importance of shielding motors (with Faraday cages), filtering electrical connections, using fieldmaps, and using short scan times with regular scanner re-shimming (recalibration). (Bottom) Details from a few exemplar scans. Individual fMRI slices are shown next to the noise-to-signal measured over their voxels. Notice the large blue, green, and yellow region in the slices from the “no shields” condition indicating high noise. After the shielding, filtering, and scanning improvements, scan runs have very low noise across all scanned fMRI slices.

ment or force application (or both). As a consequence of high fidelity and low noise measurements, we could conduct high resolution fMRI measurements of motor planning, reaching, force perception, and visually-guided force control. We present second-scale neural activation dynamics across the brain for all three. Our results demonstrate that Haptic fMRI is a mature technology that is ready for adoption by the wider motor neuroscience community.

## II. HFI-3: PERFORMANCE AND RELIABILITY

Haptic fMRI a relatively novel technique and access is limited to a few research groups around the world. A critical factor is to demonstrate reliability and performance in the long term. We present results that showcase HFI-3, a robust and capable electromagnetically actuated fMRI-compatible haptic interface. Our results summarize noise patterns for one hundred and seventy-six scans conducted using HFI-3 over a time period of about three years (Fig. 2). The scans were collected across a variety of conditions. Conditions include when the device was being used: to monitor motion; to apply regular forces; or as part of unpredictable haptic interactions. A few notable problems are discussed in Fig. 2. See the Appendix for a detailed discussion of how the temporal noise

is computed and data is analyzed.

### A. Reliable and Low Noise fMRI Measurements are Feasible with Electromagnetic Actuation

Our long-term temporal noise measurements demonstrate how specific technical upgrades to HFI-3 helped resolve noise due to electromagnetic actuation (see Fig. 2 for details). The improvements to fMRI measurement quality are tangible and evident. Moreover, the absence of specific technical components leads to clear reduction in fMRI measurement quality, as well as analog drift of the MRI calibration. The results demonstrate that high performance electromagnetic motors, when shielded with Faraday cages, emit little radiofrequency noise. The noise is further reduced by using capacitive filters for all incoming and outgoing wiring connections (see [7] for details).

### B. MRI Phantoms are Unsuitable for Testing Haptic fMRI

MRI phantoms are objects designed to mimic the properties of the human brain; they serve as a proxy to test fMRI scan fidelity when it is not feasible to scan human subjects. Our results highlight a recurrent problem with past Haptic fMRI research: that phantoms are not suitable

to estimate noise generated by candidate fMRI-compatible haptic interfaces. This is because phantoms lead to artificially low noise levels and provide misleading noise metrics for estimating whether a given device can support complex motor neuroscience experiments. Our tests with phantoms always led to very low observed noise (see Fig. 2, histogram sections marked with purple squares). This was the case even when we tested HFI-3 without shields. After observing this effect, we rejected phantom-based testing and tested our device’s noise characteristics exclusively with human subjects. A host of past research that has relied on scanning phantoms potentially requires re-evaluation.

### C. Mildly Paramagnetic Materials Affect fMRI Measurements

Having identified technical methods that brought HFI-3’s noise levels close to the fMRI baseline (for a sleeping person = 0.8%), we proceeded to perturb the measurements ourselves. We did so by placing a custom-engineered mildly paramagnetic gel (agar and NiCl<sub>2</sub>; see [24] for details) near the scanner’s coil (see Fig. 2, second block of histogram columns from the right). This test would help inform us whether it was feasible to use paramagnetic device components inside the scanner bore. Unfortunately, after collecting fMRI measurements over eight scan runs, we found that even static paramagnetic objects disrupt scan quality. While the disruption was not severe—the noise levels were lower than those obtained without a proper cage—we do not recommend developing devices or device extensions that use paramagnetic materials in the MRI bore. Particularly if they are near the scanner coil.

## III. HIGH RESOLUTION fMRI IMAGING

Having concluded that HFI-3’s design and engineering were sufficient for reliable and high fidelity fMRI measurements, we proceeded to analyze data from a few of our experiments. Our goal was to determine the level of temporal and spatial resolution that HFI-3 experiments support. Here, we present exemplar statistical analyses drawn from three specific conditions: motor planning, reaching, and visually-guided force control. These broadly cover the common interaction modalities for human subjects.

### A. fMRI Time Series for Motor Planning

To estimate the spatio-temporal resolution offered by Haptic fMRI for motor planning, we analyzed an experimental scan session of the Haptic Move-3 experiment [23]. As part of the experiment, subjects were asked to hold their hands at a specific location. They were then given a planning cue (a golden box) indicating a potential reach location. Finally, they could be given a cue to go back to rest (33% probability) or a cue to make the reach. Here, we discuss the neural activation due to motor planning (Fig. 3).

We began by using a finite impulse response (FIR) model to summarize time-series responses across the numerous repetitions of planning that a subject performed (see Appendix for details). The finite impulse response time series for each

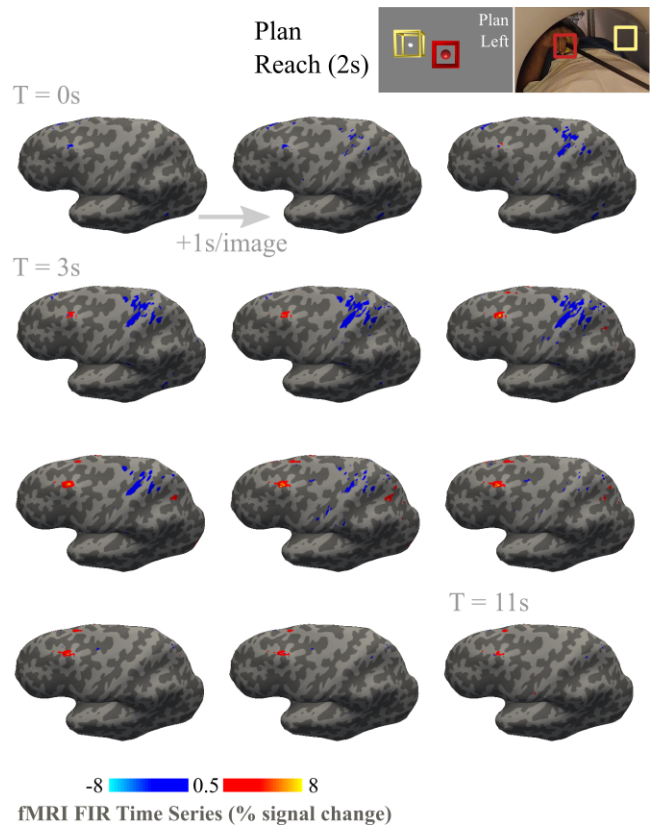


Fig. 3. High Resolution fMRI Time-Series Measurements for Reach Planning. Estimated activation for motor planning, plotted as a heatmap on an inflated brain surface. Successive brain surfaces depict neural activation with one second intervals, starting at the moment a planning cue is shown to a subject. The time series was estimated by fitting a finite impulse response model to fifty-six repetitions of the planning cue. Planning time was two seconds but the BOLD response lasts for about fifteen seconds. Images (top-right) depict the visual input (left) and task condition (right).

voxel can be plotted on a brain volume on a time-instance by time-instance basis. We did so, and obtained a sequence of brain volumes. We then plotted those on inflated brain models for the subject who performed the task. The fMRI (BOLD) neural activation pattern thus obtained allows the observation of spatio-temporal dynamics in the brain.

Neural activation for planning began with a gradual reduction in activation in somatosensory cortex, which is expected since the subject is holding still and receives no somatosensory input. Next, there is a gradual increase in activation in pre-motor regions, which is consistent with past research into motor planning. Finally, both activation patterns return to normal as the subject stops planning and goes to rest or starts the reach.

### B. fMRI Time Series for Motor Reach Execution

Similar to our analysis for motor planning, we analyzed an experimental scan session of the Haptic Move-3 experiment. Here, however, we obtained FIR time series estimates for reach execution instead of planning (Fig. 4). The actual motion is an unconstrained goal-directed reach to a position in space, with visual feedback indicating the current position of the hand (a red sphere) and the goal position (a green box).



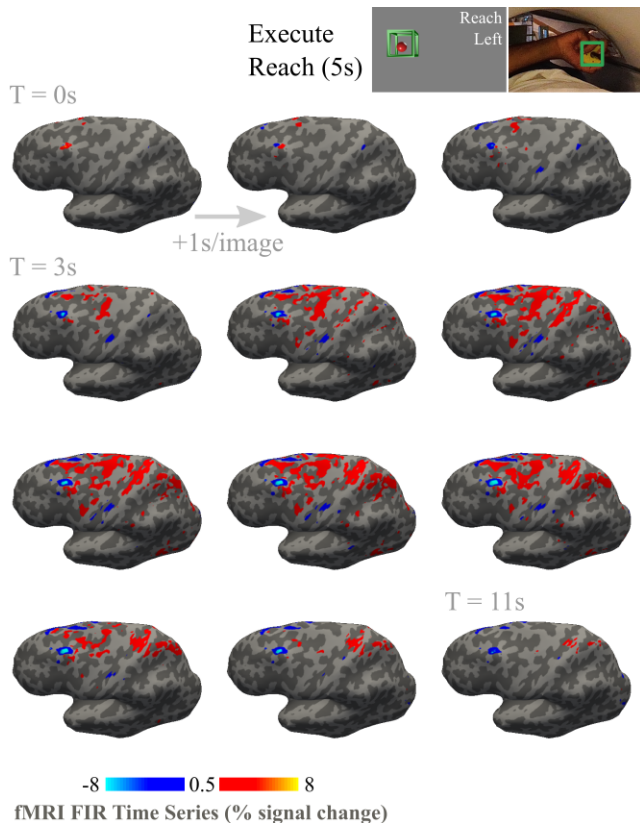


Fig. 4. High Resolution fMRI Time-Series Measurements for Reaching. Estimated activation for reach execution, plotted as a heatmap on an inflated brain surface. Successive brain surfaces depict neural activation with one second intervals, starting at the moment a reach go-cue is shown to a subject. The time series was estimated by fitting a finite impulse response model to thirty-two repetitions of reach execution. The allowed reach time was five seconds but the BOLD response lasts for about fifteen to twenty seconds. Images (top-right) depict the visual input (left) and task condition (right).

In contrast with the activation pattern observed during planning, reaching-related fMRI neural activation started in pre-motor cortex, then gradually spread towards motor cortex. This is consistent with past research indicating that neural activation for motor preparation precedes activation for movement. Next, activation appeared in somatosensory and parietal regions, which are connected with tactile perception and grasping. Finally, activation reduced in pre-motor cortex, then in motor cortex, and finally in the tactile sensory cortices. This is consistent with the nature of the BOLD impulse response.

### C. fMRI Time Series for Visually-Guided Force Control

Finally, we repeated our analysis for a visually-guided force control experiment (Fig. 5). Here, subjects held a lever attached to HFI-3’s end effector and applied forces. Visual feedback was provided in the form of a blank screen of a suitable color (see Fig. 5). Subjects were required to hold a constant force of either 3.5, 4, or 5.5N for eight seconds. We obtained FIR responses assuming a linear increase in peak BOLD response magnitude with the force level.

We present the data aligned to the end of the force application procedure, which is more reliable. This avoids

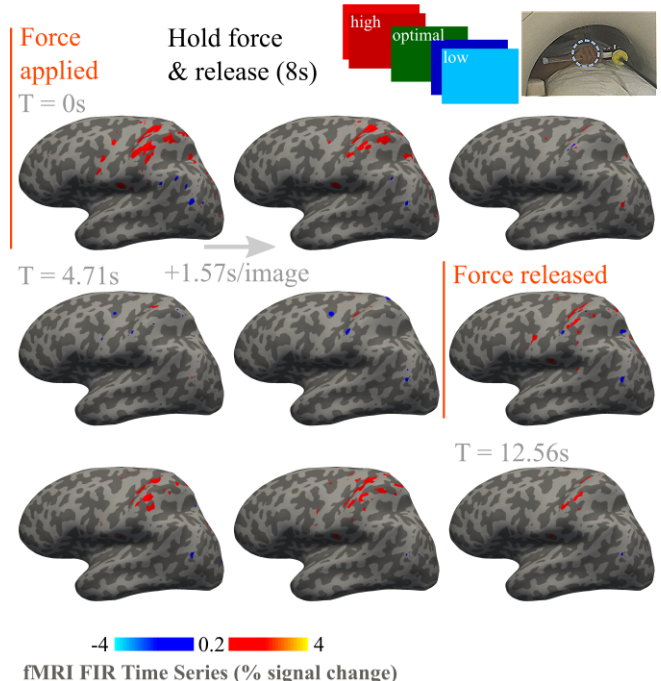


Fig. 5. High Resolution fMRI Time-Series Measurements for Force Control. Estimated activation for force control with a lever, plotted as a heatmap on an inflated brain surface. Successive brain surfaces depict neural activation with about one and a half second intervals, starting at the moment a subject is applying a stable force (disregarding early and irregular transients). The time series was estimated by fitting a finite impulse response model to thirty-two repetitions of the force control task. Subjects were required to hold a force for eight seconds using a color cue (blank colored screen) for feedback. The BOLD response was faster than experiments with extensive visual input and seems to subside six to nine seconds after forces change. Images (top-right) depict the visual input (left) and task condition (right).

transients associated with the time when a subject is adjusting their force after the force application cue appears. We note that the force control activation is similar to activation for an alternative force perception experiment detailed earlier [9].

Observing the fMRI BOLD response, we found activation in motor and somatosensory cortex when the subjects were applying forces, and when they stopped applying forces. This is consistent with past research. We note that the fMRI activation seems to be influenced by changes in force and, consequently, visual input. Moreover, the timescale of BOLD responses is shorter than motor planning and reaching, which—unlike this experiment—have an extensive visual component. Identifying the root cause is an interesting area for future research.

## IV. CONCLUSION

To conclude, we demonstrate that our electromagnetically actuated Haptic fMRI Interface, HFI-3, can be operated reliably over a span of years to consistently support high fidelity fMRI motor neuroimaging experiments. HFI-3’s performance demonstrates two-ended fMRI-compatibility: electromagnetic actuation does not disrupt fMRI measurements, and the MRI scanner’s strong magnetic field does not affect

the electromagnetic actuators. In the process, we also set expectations for high fidelity fMRI measurements during motor neuroimaging experiments.

By demonstrating high fidelity fMRI measurements in the brain’s motor regions, our results promise to help generalize and advance preliminary fMRI experiments studying pre-motor, motor [25], [16], [26], somatosensory [27], parietal [28], and visual [29] cortex. They also promise to help advance the study of motor pathologies [30], [31] and motor rehabilitation [32], [33], [34], [35], [36] by allowing clinicians to observe how therapy affects neural circuits in real-time.

## APPENDIX

**fMRI Scanning:** All fMRI scans were conducted at Stanford University’s Center for Cognitive and Neurobiological Imaging on a GE Discovery MR750 3 Tesla MRI scanner, with a 32 channel Nova Medical head coil. The scan protocol was gradient echo EPI with a 16cm field of view sampled at a 64x64 resolution (2.5x2.5x2.5 mm<sup>3</sup> voxels), a 1.57s repetition time, a 28ms echo time, and a 72° flip angle. Settings were chosen to trade off brain-volume scanned for improved temporal noise [37]. All scan runs were preceded by 2<sup>nd</sup>-order polynomial shimming and were sandwiched by fieldmap scans. After scanning, the fMRI images were slice time corrected, motion corrected (SPM), spatially undistorted using fieldmaps, and analyzed to compute temporal signal-to-noise. A subject-customized bite-bar minimized head motion. All runs (6-10min each) had frame-to-frame head motion >0.1mm or overall head motion >1mm.

**fMRI Analysis:** Temporal noise-to-signal computations used the median neural response distribution obtained by regressing out a line from each voxels time series, computing the absolute value of the difference between successive time points, computing the median of these absolute differences, dividing the result by the mean of the original time series, and then multiplying by 100. Surface registration was done using Freesurfer, and all surface images were plotted using Freeview. Freeview smoothed the surface plots while rendering (4 steps for planning and reaching data; 8 steps for force data).

**Estimating fMRI Impulse Response Time Series and R<sup>2</sup>:** fMRI measures changes in blood oxygenation induced by neural metabolic activity [38], [15], which have a slower time course than neural computation and persist long after sensory stimuli and motor tasks terminate. Such persistent responses cause raw fMRI measurements to overlap in experiments where consecutive task conditions are not separated by large time-intervals. Separating task conditions by large time-intervals, however, makes fMRI runs very long, which can induce a variety of unwanted artifacts related to MRI scanner calibration drift, neural adaptation, or subject attention lapses, microsleep and exhaustion. Instead, we optimized our experiments to ensure reliable motor task execution [23], which caused fMRI measurements for different task conditions to overlap.

We segregated neural activation for individual tasks using a finite impulse response (FIR) model (implemented using GLMdenoise [39]). The FIR model works by associating each task type with a unique time course and segregates time courses while assuming that overlapping responses sum linearly. fMRI signal linearity, however, is an active area of research [38], [40], [41]. As such, we randomized inter-task delays and randomly ordered tasks, which made the model’s time series match anatomical expectations based on past research (read [9], [42] for more details). When tasks were closely spaced in time, as with planning and motion, this method was noisy. The later parts of the planning FIR response, which overlaps with motion, is thus less reliable.

**Human Subjects:** Subjects were healthy and right-handed with no history of motor disorders. Informed consent was obtained in advance on a protocol approved by the Institutional Review Board (IRB) at Stanford University.

## ACKNOWLEDGMENTS

We gratefully acknowledge Hari Ganti, Paul Quigley, and Michelle Yu for their assistance in designing and conducting parts of the experiments. We thank Kendrick Kay for assisting with fMRI analysis. Finally, we thank Laima Baltusis and Robert Dougherty for helping develop fMRI scanning and data processing protocols.

## REFERENCES

- [1] J. Diedrichsen, Y. Hashambhoy, T. Rane, and R. Shadmehr, “Neural correlates of reach errors,” *The Journal of Neuroscience*, vol. 25, no. 43, pp. 9919–9931, 2005.
- [2] J. Hidler, T. Hodics, B. Xu, B. Dobkin, and L. Cohen, “Mr compatible force sensing system for real-time monitoring of wrist moments during fMRI testing,” *Journal of neuroscience methods*, vol. 155, no. 2, pp. 300–307, 2006.
- [3] R. Gassert, L. Dovat, O. Lamberg, Y. Ruffieux, D. Chapuis, G. Ganesh, E. Burdet, and H. Bleuler, “A 2-dof fMRI compatible haptic interface to investigate the neural control of arm movements,” in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*. IEEE, 2006, pp. 3825–3831.
- [4] R. Gassert, R. Moser, E. Burdet, and H. Bleuler, “Mri/fMRI-compatible robotic system with force feedback for interaction with human motion,” *Mechatronics, IEEE/ASME Transactions on*, vol. 11, no. 2, pp. 216–224, 2006.
- [5] A. Hribar, B. Koritnik, and M. Munih, “Phantom haptic device upgrade for use in fMRI,” *Medical and Biological Engineering and Computing*, vol. 47, pp. 677–684, 2009.
- [6] N. Yu, N. Estévez, M. Hepp-Reymond, S. Kollias, and R. Riener, “fMRI assessment of upper extremity related brain activation with an mri-compatible manipulandum,” *International journal of computer assisted radiology and surgery*, vol. 6, no. 3, pp. 447–455, 2011.
- [7] S. Menon, G. Brantner, C. Aholt, K. Kay, and O. Khatib, “Haptic fMRI : Combining functional neuroimaging with haptics for studying the brain’s motor control representation,” in *Proceedings of the 13th Annual Conference of the IEEE Engineering in Medicine and Biology Society*, July 2013, pp. 4137–42.
- [8] S. Menon, A. Stanley, J. Zhu, A. Okamura, and O. Khatib, “Mapping stiffness perception in the brain with an fMRI-compatible particle-jamming haptic interface,” in *Proceedings of the 14th Annual Conference of the IEEE Engineering in Medicine and Biology Society*, August 2014.
- [9] S. Menon, H. Ganti, and O. Khatib, “Using haptic fMRI to enable interactive motor neuroimaging experiments,” *Springer Tracts in Experimental Robotics*, vol. 81, 2014.
- [10] A. Erwin, M. O’Malley, D. Rens, and F. Sergi, “Kinesthetic feedback during 2dof wrist movements via a novel mr-compatible robot,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2016.

- [11] K. S. Hale and K. M. Stanney, "Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations," *Computer Graphics and Applications, IEEE*, vol. 24, no. 2, pp. 33–39, March–April 2004.
- [12] J. K. Salisbury, F. Conti, and F. Barbagli, "Haptic rendering: Introductory concepts," *IEEE Computer Graphics and Applications*, vol. 24, no. 2, pp. 24–32, March 2004.
- [13] F. Conti and O. Khatib, "Spanning large workspaces using small haptic devices," *Proc. of the Eurohaptics on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 183–188, Mar. 2005.
- [14] —, "A new actuation approach for haptic interface design," *The International Journal of Robotics Research*, vol. 28, no. 6, pp. 834–848, 2009.
- [15] N. K. Logothetis, "What we can do and what we cannot do with fMRI," *Nature*, vol. 453, no. 7197, pp. 869–878, Jun 2008.
- [16] J. D. Meier, T. N. Aflalo, S. Kastner, and M. S. A. Graziano, "Complex organization of human primary motor cortex: A high-resolution fMRI study," *Journal of Neurophysiology*, vol. 100, pp. 1800–1812, 2008.
- [17] J. Vogau, A. Wingert, J. Plante, S. Dubowsky, M. Hafez, and D. Kacher, "Manipulation in mri devices using electrostrictive polymer actuators: with an application to reconfigurable imaging coils," in *IEEE International Conference on Robotics and Automation*, 2004, pp. 2498–2504.
- [18] E. Burdet, R. Gassert, G. Gowrishankar, and H. Bleuler, "fMRI compatible haptic interfaces to investigate human motor control," *Experimental Robotics IX*, vol. 21, pp. 25–34, 2006.
- [19] S. Klare, A. Peer, and M. Buss, "Development of a 3 dof mr-compatible haptic interface for pointing and reaching movements," *Lecture Notes in Computer Science*, vol. 6192, pp. 211–218, 2010.
- [20] D. Chapuis, R. Gassert, G. Gowrishankar, E. Burdet, and H. Bleuler, "Investigation of a cable transmission for the actuation of mr compatible haptic interfaces," in *Proc. of Biomedical Robotics and Biomechanics*, 2006, pp. 426–431.
- [21] T. Massie and J. Salisbury, "The phantom haptic interface: A device for probing virtual objects," in *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, vol. 55-1. IOS Press, 1994, pp. 295–300.
- [22] M. Kostic, D. Popovic, and M. Popovic, "Influence of planar manipulation to the hand trajectory during point to point movement," in *IEEE International Conference on Rehabilitation Robotics*, July 2011, pp. 1–4.
- [23] S. Menon, M. Yu, K. Kay, and O. Khatib, "Haptic fMRI : Accurately estimating neural responses in motor, pre-motor, and somatosensory cortex during complex motor tasks," in *Proceedings of the 14th Annual Conference of the IEEE Engineering in Medicine and Biology Society*, August 2014.
- [24] S. Menon, P. Quigley, M. Yu, and O. Khatib, "Haptic fMRI : Using classification to quantify task-correlated noise during goal-directed reaching motions," in *Proceedings of the 14th Annual Conference of the IEEE Engineering in Medicine and Biology Society*, August 2014.
- [25] M. Lotze, P. Montoya, M. Erb, E. Hülsmann, H. Flor, U. Klose, N. Birbaumer, and W. Grodd, "Activation of cortical and cerebellar motor areas during executed and imagined hand movements: An fMRI study," *Journal of Cognitive Neuroscience*, vol. 11, no. 5, pp. 491–501, 1999.
- [26] R. Shadmehr, M. A. Smith, and J. W. Krakauer, "Error correction, sensory prediction, and adaptation in motor control," *Annual Review of Neuroscience*, vol. 33, no. 1, pp. 89–108, 2010.
- [27] H. Hämäläinen, J. Hiltunen, and I. Titievskaja, "fMRI activations of si and sii cortices during tactile stimulation depend on attention," *Neuroreport*, vol. 11, no. 8, pp. 1673–1676, 2000.
- [28] J. Connolly, R. Andersen, and M. Goodale, "fMRI evidence for a 'parietal reach region' in the human brain," *Experimental Brain Research*, vol. 153, no. 2, pp. 140–145, 2003.
- [29] S. Courtney, L. Ungerleider, et al., "What fMRI has taught us about human vision," *Current opinion in neurobiology*, vol. 7, no. 4, p. 554, 1997.
- [30] P. Rossini, C. Caltagirone, A. Castriota-Scanderbeg, P. Cicinelli, C. Del Gratta, M. Demartin, V. Pizzella, R. Traversa, and G. Romani, "Hand motor cortical area reorganization in stroke: a study with fMRI, meg and tcs maps," *Neuroreport*, vol. 9, no. 9, pp. 2141–2146, 1998.
- [31] N. Ward, M. Brown, A. Thompson, and R. Frackowiak, "Neural correlates of motor recovery after stroke: a longitudinal fMRI study," *Brain*, vol. 126, no. 11, pp. 2476–2496, 2003.
- [32] H. Sveistrup, "Motor rehabilitation using virtual reality," *Journal of NeuroEngineering and Rehabilitation*, vol. 1, no. 1, p. 10, 2004.
- [33] J. Broeren, M. Rydmark, A. Bjrkdahl, and K. S. Sunnerhagen, "Assessment and training in a 3-dimensional virtual environment with haptics: A report on 5 cases of motor rehabilitation in the chronic stage after stroke," *Neurorehabilitation and Neural Repair*, vol. 21, no. 2, pp. 180–189, March–April 2007.
- [34] J. W. Krakauer, "Motor learning: its relevance to stroke recovery and neurorehabilitation," *Current opinion in neurology*, vol. 19, no. 1, pp. 84–90, 2006.
- [35] S. R. Zeiler and J. W. Krakauer, "The interaction between training and plasticity in the post-stroke brain," *Current opinion in neurology*, vol. 26, no. 6, p. 609, 2013.
- [36] A. U. Pehlivan, F. Sergi, A. Erwin, N. Yozbatiran, G. E. Francisco, and M. K. O'Malley, "Design and validation of the ricewrist-s exoskeleton for robotic rehabilitation after incomplete spinal cord injury," *Robotica*, vol. 32, no. 08, pp. 1415–1431, 2014.
- [37] K. Murphy, J. Bodurka, and P. A. Bandettini, "How long to scan? the relationship between fMRI temporal signal to noise ratio and necessary scan duration," *NeuroImage*, vol. 34, no. 2, pp. 565 – 574, 2007.
- [38] N. K. Logothetis and B. A. Wandell, "Interpreting the bold signal," *Annu. Rev. Physiol.*, vol. 66, pp. 735–769, 2004.
- [39] K. Kay, A. Rokem, J. Winawer, R. Dougherty, and B. Wandell, "Glm denoise: a fast, automated technique for denoising task-based fMRI data," *Frontiers in Neuroscience*, vol. 7, no. 247, 2013.
- [40] G. M. Boynton, S. A. Engel, G. H. Glover, and D. J. Heeger, "Linear systems analysis of functional magnetic resonance imaging in human v1," *The Journal of Neuroscience*, vol. 16, no. 13, pp. 4207–4221, 1996. [Online]. Available: <http://www.jneurosci.org/content/16/13/4207.abstract>
- [41] A.-L. Lin, P. T. Fox, J. Hardies, T. Q. Duong, and J.-H. Gao, "Nonlinear coupling between cerebral blood flow, oxygen consumption, and ATP production in human visual cortex," *Proceedings of the National Academy of Sciences*, vol. 107, no. 18, pp. 8446–8451, 2010. [Online]. Available: <http://www.pnas.org/content/107/18/8446.abstract>
- [42] D. Rosenbaum, *Human motor control*. Academic Press, 2009.