NATIONAL SCIENCE FOUNDATION
2415 Eisenhower Avenue
Alexandria, Virginia 22314

OFFICE OF THE
GENERAL COUNSEL

April 2, 2021

Via e-mail

Case #2021-095F

Mr. Russ Kick
Rise for Animals
333 Washington Street, Suite 850
Boston, Massachusetts 02108

Dear Mr. Kick:

This letter is in response to your Freedom of Information Act (FOIA) request that the National Science Foundation (NSF) received on November 17, 2020. In your request on behalf of Rise for Animals, you sought a copy of the following records pertaining to NSF award 1558151/1557886:

1) The full proposal, including all appendices, attachments, and accompanying documents.

2) The notice of award.

3) The most recent renewal proposal, if any.

4) The three most recent amendments.

5) All annual project reports.

6) The final report, closing memo, letter, etc. memorializing all site visits by NSF related to this grant.

Telephone (703) 292-8060 FAX (703) 292-9483

7) All notifications sent to NSF falling under Proposal and Award Policies and Procedures Guide, Chapter VII(A)(2): "Grantee Notifications to NSF."

8) All notifications sent to NSF falling under PAPPG Chapter VII(B): "Changes in Project Direction or Management."

9) All IACUC approval letters as discussed in PAPPG, Chapter XI(B)(3)(b)(ii): "When an additional IACUC approval is required, the organization must provide to the cognizant NSF Program Officer a signed copy of a new IACUC approval letter indicating approval of the covered activities and explicitly referencing the title of the award."

After a thorough search, no records were located for items 3, 6, 7, and 8 of your request. Enclosed, please find the responsive records for the remaining items. Proprietary information (trade secrets, commercial or financial information, EIN/TID, TIN numbers, pending and non-Federal grants, details of process methods and innovation) has been withheld under the provisions of Exemption (b)(4) of the FOIA. Personal information (Names, SSN, personal email and home address, home phone number, EIN/TID, TIN numbers, date/place of birth, bios, and individual salaries) has been withheld wherever it appears under the privacy protection of Exemption (b)(6) of the FOIA.

Your right to appeal this response is set forth in Section 612.9 of the NSF FOIA regulation (copy enclosed). Your appeal must be postmarked or electronically transmitted within 90 days of the date of the response to your request.

If you need any further assistance or would like to discuss any aspect of your request, please do not hesitate to contact our FOIA Public Liaison at 703-292-2289. Additionally, you may contact the Office of Government Information Services (OGIS) which was created to offer mediation services to resolve disputes between FOIA requesters and Federal agencies as a non-exclusive alternative to litigation. Using OGIS services does not affect your right to pursue litigation. If you are requesting access to your own records (which is considered a Privacy Act request), you should know that OGIS does not have the authority to handle requests made under the Privacy Act of 1974. You may contact OGIS in any of the following ways:

National Archives and Records Administration
Office of Government Information Services
8601 Adelphi Road - OGIS
College Park, Maryland 20740-6001
E-mail: ogis@nara.gov
Web: https://www.archives.gov/ogis
Telephone: 202-741-5770
Facsimile: 202-741-5769
Toll-free: 1-877-684-6448

There is no fee for FOIA services in this instance in accordance with 5 U.S.C. § 552(a)(4)(A)(i) et seq. Should you have any questions regarding this response, please contact me at 703-292-2289 or via e-mail at jguz@nsf.gov. Thank you for your interest in the National Science Foundation.

Sincerely,

/s/

Justin Guz
Government Information Specialist

Enclosures

NATIONAL SCIENCE FOUNDATION
Grant Letter

Award:1558151 **PI Name:**Buneo, Christopher

AWARD NOTICE

Award Date: September 15, 2016
Award No. (FAIN): 1558151
Proposal No.: 1558151
Managing Division Abbreviation: IOS

Tamara Deuser
Manager, Office of Research & CreativeActivities
Arizona Board of Regents
Arizona State University
ORSPA
660 South Mill Avenue, Suite 310
Tempe, AZ 85281-6011
DUNS ID: 943360412

Dear Ms. Deuser:

The National Science Foundation hereby awards a grant of $721,492 to Arizona Board of Regents Arizona State University for support of the project described in the proposal referenced above as modified by revised budget dated July 13, 2016. This award is expected to total $1,271,492.

This project, entitled "Collaborative Research: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network," is under the direction of
Christopher A. Buneo, in collaboration with the following proposals

Proposal No: PI Name/Institution

1557886 Bijan .
Pesaran, New York University

.

This award starts September 15, 2016 and ends August 31, 2021.

This is a continuing grant which has been approved on scientific / technical merit. Contingent on the availability of funds and the scientific progress of the project, NSF expects to continue support at approximately the following level:

FY 2017	$200,000
FY 2019	$250,000
FY 2020	$100,000

The scientific / technical progress of the project is documented through submission and approval of annual and final project reports to NSF. Such reports are to be submitted electronically via NSF's Research.gov web portal [http://www.research.gov/]. Information regarding the specific due dates of such reports also is available through Research.gov.

This grant is awarded pursuant to the authority of the National Science Foundation Act of 1950, as amended (42 U.S.C. 1861-75) and is subject to NSF Grant General Conditions (GC-1), dated January 25, 2016, available at http://www.nsf.gov/awards/managing/general_conditions.jsp.

This award is subject to the Uniform Administrative Requirements, Cost Principles and Audit Requirements for Federal Awards (Uniform Guidance). NSF's implementation of the Uniform Guidance is contained in the Grant Conditions referenced in this award.

This institution is a signatory to the Federal Demonstration Partnership (FDP) Phase VI Agreement which requires active institutional participation in new or ongoing FDP demonstrations and pilots. and the following terms and conditions:

This award is subject to the Federal Funding Accountability and Transparency Act (FFATA) award term entitled, Reporting Subawards and Executive Compensation, which has been incorporated into the NSF Terms and Conditions referenced above.

If the awardee has any questions related to the pre-populated data associated with this award in the FFATA Subaward Reporting System, such questions should be submitted to: FFATAReporting@nsf.gov or by phone to: (800) 673-6188.

This award is made in accordance with the provisions of NSF Solicitation 13-600, Division of Integrative Organismal Systems.

Fiscal Year 2017 and 2018 budgets have been combined in this award. It is still the grantee's responsibility to submit an annual project report in accordance with the NSF Grant General Conditions (GC-1), dated January 25, 2016.

Please view the project reporting requirements for this award at the following web address [https://reporting.research.gov/fedAwardId/1558151].

The attached budget indicates the amounts, by categories, on which NSF has based its support.

The indirect cost rate(s) for this award is/are :
Item Name
Indirect Cost Rate

Salary/Travel/Supplies 54.5000%
These rates are at the time of award and are based upon the budget submitted to the NSF. It does not include any out-year adjustments. The NSF will not modify awards simply to correct indirect cost rates cited in the award notice. See the Award and Administration Guide (AAG) Chapter V.A.3.a. for guidance on re-budgeting authority.

The cognizant NSF program official for this grant is Edda (Floh) Thiels, (703) 292-8167.
The cognizant NSF grants official contact is Staci S. Jenkins, (703) 292-5042.

Sincerely,

Aprile N. Roberson
Grants and Agreements Officer

CFDA No. 47.074, Biological Sciences
asu.awards@asu.edu

IOS-1558151 000
SUMMARY PROPOSAL BUDGET

Person MOS	cal	acad	sumr	Funds granted By NSF
A. (1.00) Total Senior personnel	(b) (4), (b) (6) [redacted]			
B. Other Personnel				
1. (1.00) Post Doctoral associates				
2. (1.00) Other professionals				
3. (3.00) Graduate students				
4. (0.00) Secretarial-clerical				
5. (0.00) Undergraduate students				
6. (0.00) Other				
Total salaries and wages (A+B)				
C. Fringe benefits (if charged as direct cost				
Total salaries wages and fringes (A+B+C)				

D. Total permanent equipment	$232,000
E. Travel	
1. Domestic	$16,690
2. Foreign	$3,600
F. Total participant support costs	$0
G. Other direct costs	
1. Materials and supplies	$80,396
2. Publication costs/page charges	$1,250
3. Consultant services	$0
4. Computer (ADPE) services	$0
5. Subcontracts	$0
6. Other	$46,752
Total other direct costs	$128,398
H. Total direct costs (A through G)	(b)(4) [redacted]
I. Total indirect costs	
(For information on the rate used, please refer to the award notice)	
J. Total direct and indirect costs (H+I)	$721,492
K. Small Business Fee	$0
L. Amount of this request (J) or (J+K) $721,492	
M. Cost sharing	$0

NATIONAL SCIENCE FOUNDATION

Grant Letter

Award:1557886 **PI Name:**Pesaran, Bijan

AWARD NOTICE

Award Date:	September 15, 2016
Award No. (FAIN):	1557886
Proposal No.:	1557886
Managing Division Abbreviation:	IOS

Ms. Nancy Daneau
Director, Sponsored Programs
New York University
70 Washington Square S
New York, NY 10012-1019
DUNS ID: 041968306

Dear Ms. Daneau:

The National Science Foundation hereby awards a grant of $126,893 to New York University for support of the project described in the proposal referenced above as modified by revised budget dated July 15, 2016. This award is expected to total $242,243.

This project, entitled "Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network," is under the direction of Bijan Pesaran, in collaboration with the following proposals

Proposal No: PI Name/Institution

1558151 Christopher A. Buneo, Arizona Board of Regents Arizona State University

.

This award starts September 15, 2016 and ends August 31, 2021.

This is a continuing grant which has been approved on scientific / technical merit. Contingent on the availability of funds and the scientific progress of the project, NSF expects to continue support at approximately the following level:

FY 2017	$35,350
FY 2019	$55,000
FY 2020	$25,000

The scientific / technical progress of the project is documented through submission and approval of annual and final project reports to NSF. Such reports are to be submitted electronically via NSF's Research.gov web portal [http://www.research.gov/]. Information regarding the specific due dates of such reports also is available through Research.gov.

This grant is awarded pursuant to the authority of the National Science Foundation Act of 1950, as amended (42 U.S.C. 1861-75) and is subject to NSF Grant General Conditions (GC-1), dated January 25, 2016, available at http://www.nsf.gov/awards/managing/general_conditions.jsp.

This award is subject to the Uniform Administrative Requirements, Cost Principles and Audit Requirements for Federal Awards (Uniform Guidance). NSF's implementation of the Uniform Guidance is contained in the Grant Conditions referenced in this award.

This institution is a signatory to the Federal Demonstration Partnership (FDP) Phase VI Agreement which requires active institutional participation in new or ongoing FDP demonstrations and pilots. and the following terms and conditions:

This award is subject to the Federal Funding Accountability and Transparency Act (FFATA) award term entitled, Reporting Subawards and Executive Compensation, which has been incorporated into the NSF Terms and Conditions referenced above.

If the awardee has any questions related to the pre-populated data associated with this award in the FFATA Subaward Reporting System, such questions should be submitted to: FFATAReporting@nsf.gov or by phone to: (800) 673-6188.

This award is made in accordance with the provisions of NSF Solicitation 13-600, Division of Integrative Organismal Systems.

Fiscal Year 2017 and 2018 budgets have been combined in this award. It is still the grantee's responsibility to submit an annual project report in accordance with the NSF Grant General Conditions (GC-1), dated January 25, 2016.

Please view the project reporting requirements for this award at the following web address [https://reporting.research.gov/fedAwardId/1557886].

The attached budget indicates the amounts, by categories, on which NSF has based its support.

The indirect cost rate(s) for this award is/are :
Item Name
Indirect Cost Rate

Modified Total Direct Costs 58.5000%
These rates are at the time of award and are based upon the budget submitted to the NSF. It does not include any out-year adjustments. The NSF will not modify awards simply to correct indirect cost rates cited in the award notice. See the Award and Administration Guide (AAG) Chapter V.A.3.a. for guidance on re-budgeting authority.

The cognizant NSF program official for this grant is Edda (Floh) Thiels, (703) 292-8167.
The cognizant NSF grants official contact is Staci S. Jenkins, (703) 292-5042.

Sincerely,

Aprile N. Roberson
Grants and Agreements Officer

CFDA No. 47.074, Biological Sciences
osp.agency@nyu.edu

IOS-1557886 000
SUMMARY PROPOSAL BUDGET

Person MOS	cal	acad	sumr	Funds granted By NSF
A. (1.00) Total Senior personnel	(b)(4), (b)(6) [redacted]			
B. Other Personnel				
1. (0.00) Post Doctoral associates				
2. (0.00) Other professionals				
3. (0.00) Graduate students				
4. (0.00) Secretarial-clerical				
5. (0.00) Undergraduate students				
6. (0.00) Other				
Total salaries and wages (A+B)				
C. Fringe benefits (if charged as direct cost				
Total salaries wages and fringes (A+B+C)				
D. Total permanent equipment				$5,000
E. Travel				
1. Domestic				$2,503
2. Foreign				$0

F. Total participant support costs	$0
G. Other direct costs	
1. Materials and supplies	$0
2. Publication costs/page charges	$0
3. Consultant services	$0
4. Computer (ADPE) services	$0
5. Subcontracts	$0
6. Other	$0
Total other direct costs	$0
H. Total direct costs (A through G)	(b)(4), (b)(6) [redacted]
I. Total indirect costs	
(For information on the rate used, please refer to the award notice)	
J. Total direct and indirect costs (H+I)	$126,893
K. Small Business Fee	$0
L. Amount of this request (J) or (J+K)	
$126,893	
M. Cost sharing	$0

Not for distribution

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 15-1

NSF 13-600 08/07/15

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)

IOS - ACTIVATION

FOR NSF USE ONLY

NSF PROPOSAL NUMBER

1558151

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
08/07/2015	1	08090000 IOS	7713	943360412	08/07/2015 9:50pm

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN): 860196696

SHOW PREVIOUS AWARD NO. IF THIS IS
☐ A RENEWAL
☐ AN ACCOMPLISHMENT-BASED RENEWAL

IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE: Arizona State University

AWARDEE ORGANIZATION CODE (IF KNOWN): 0010819000

ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE:
Arizona State University
ORSPA
Tempe, AZ. 852816011

NAME OF PRIMARY PLACE OF PERF: Arizona State University

ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE:
Arizona State University
AZ ,852876011 ,US.

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS

☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT: Collaborative Research: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ [redacted]	60 months	05/01/16	[redacted]

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
☐ BEGINNING INVESTIGATOR (GPG I.G.2)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☒ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date Planned
PHS Animal Welfare Assurance Number A3217-01
☒ FUNDING MECHANISM Research - other than RAPID or EAGER
☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number ____
Exemption Subsection ____ or IRB App. Date ____
☒ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
GM
☒ COLLABORATIVE STATUS
A collaborative proposal from multiple organizations (GPG II.D.4.b)

PI/PD DEPARTMENT: Biological & Health Systems Engineering

PI/PD FAX NUMBER: 480-727-7624

PI/PD POSTAL ADDRESS:
PO Box 879709
TEMPE, AZ 852873503
United States

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Email Address
PI/PD NAME Christopher A Buneo	PhD	1996	480-727-0841	christopher.buneo@asu.edu
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

CERTIFICATION PAGE

Certification for Authorized Organizational Representative (or Equivalent) or Individual Applicant

By electronically signing and submit ing this proposal, the Authorized Organizational Representative (AOR) or Individual Applicant is: (1) cer ifying hat statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Fur her, the applicant is hereby providing certifications regarding conflict of interest (when applicable), drug-free workplace, debarment and suspension, lobbying activities (see below), nondiscrimination, flood hazard insurance (when applicable), responsible conduct of research, organiza ional support, Federal tax obligations, unpaid Federal tax liability, and criminal convictions as set forth in the NSF Proposal & Award Policies & Procedures Guide,Part I: the Grant Proposal Guide (GPG). Willful provision of false information in his applica ion and its supporting documents or in reports required under an ensuing award is a criminal offense (U.S. Code, Title 18, Sec ion 1001).

Certification Regarding Conflict of Interest

The AOR is required to complete certifications stating that he organization has implemented and is enforcing a written policy on conflicts of interest (COI), consistent wi h the provisions of AAG Chapter IV.A.; that, to he best of his/her knowledge, all financial disclosures required by the conflict of interest policy were made; and that conflicts of interest, if any, were, or prior to the organization's expenditure of any funds under he award, will be, satisfactorily managed, reduced or eliminated in accordance with the organiza ion's conflict of interest policy. Conflicts that cannot be satisfactorily managed, reduced or eliminated and research that proceeds without the imposition of conditions or restrictions when a conflict of interest exists, must be disclosed to NSF via use of the No ifications and Requests Module in FastLane.

Drug Free Work Place Certification

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent), is providing the Drug Free Work Place Certification contained in Exhibit II-3 of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes (b) (4) [redacted]

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) or Individual Applicant is providing the Debarment and Suspension Certification contained in Exhibit II-4 of the Grant Proposal Guide.

Certification Regarding Lobbying

This cer ification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for he United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned cer ifies, to the best of his or her knowledge and belief, that:
(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or coopera ive agreement.
(2) If any funds o her than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connec ion with his Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instruc ions.
(3) The undersigned shall require that the language of this cer ification be included in the award documents for all subawards at all iers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This cer ification is a material representa ion of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Certification Regarding Nondiscrimination

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) is providing he Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Grant Proposal Guide.

Certification Regarding Flood Hazard Insurance

Two sec ions of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:
(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:
(1) for NSF grants for he construc ion of a building or facility, regardless of the dollar amount of the grant; and
(2) for o her NSF grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

Certification Regarding Responsible Conduct of Research (RCR)
(This certification is not applicable to proposals for conferences, symposia, and workshops.)

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative is certifying that, in accordance with the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.B., the ins itution has a plan in place to provide appropriate training and oversight in he responsible and ethical conduct of research to undergraduates, graduate students and postdoctoral researchers who will be supported by NSF to conduct research.
The AOR shall require that the language of this cer ification be included in any award documents for all subawards at all tiers.

CERTIFICATION PAGE - CONTINUED

Certification Regarding Organizational Support

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) is certifying that there is organizational support for the proposal as required by Section 526 of the America COMPETES Reauthoriza ion Act of 2010. This support extends to he portion of the proposal developed to sa isfy the Broader Impacts Review Criterion as well as the Intellectual Merit Review Criterion, and any additional review criteria specified in the solicitation. Organizational support will be made available, as described in the proposal, in order to address the broader impacts and intellectual merit activities to be undertaken.

Certification Regarding Federal Tax Obligations

When the proposal exceeds $5,000,000, the Authorized Organiza ional Representative (or equivalent) is required to complete the following cer ification regarding Federal tax obligations. By electronically signing the Certifica ion pages, he Authorized Organizational Representative is certifying that, to the best of their knowledge and belief, the proposing organiza ion:
(1) has filed all Federal tax returns required during the three years preceding this certifica ion;
(2) has not been convicted of a criminal offense under the Internal Revenue Code of 1986; and
(3) has not, more than 90 days prior to this certification, been notified of any unpaid Federal tax assessment for which the liability remains unsa isfied, unless the assessment is the subject of an installment agreement or offer in compromise hat has been approved by he Internal Revenue Service and is not in default, or the assessment is the subject of a non-frivolous administra ive or judicial proceeding.

Certification Regarding Unpaid Federal Tax Liability

When the proposing organization is a corporation, he Au horized Organiza ional Representative (or equivalent) is required to complete the following certification regarding Federal Tax Liability:

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) is certifying that the corporation has no unpaid Federal tax liability hat has been assessed, for which all judicial and administrative remedies have been exhausted or lapsed, and that is not being paid in a timely manner pursuant to an agreement with the au hority responsible for collecting he tax liability.

Certification Regarding Criminal Convictions

When the proposing organization is a corporation, he Au horized Organiza ional Representative (or equivalent) is required to complete the following certification regarding Criminal Convictions:

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) is certifying that the corporation has not been convicted of a felony criminal viola ion under any Federal law within the 24 months preceding the date on which the certification is signed.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME Lindsey Bosak	Electronic Signature	Aug 7 2015 6:03PM

TELEPHONE NUMBER	EMAIL ADDRESS	FAX NUMBER
480-965-7874	lindsey.bosak@asu.edu	

Not for distribution

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 15-1	FOR NSF USE ONLY
NSF 13-600 08/07/15	NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) IOS - MODULATION	1557886

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
08/07/2015	1	08090000 IOS	7714	041968306	08/07/2015 9:51pm

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)	SHOW PREVIOUS AWARD NO. IF THIS IS	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY?
135562308	☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
New York University	New York University 70 WASHINGTON SQUARE S NEW YORK, NY. 100121019
AWARDEE ORGANIZATION CODE (F KNOWN) 0027854000	
NAME OF PRIMARY PLACE OF PERF New York University	ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE New York University NY ,100121019 ,US.

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions) ☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ (b) (4) [redacted]	60 months	05/01/16	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG I.G.2)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
- ☐ HISTORIC PLACES (GPG II.C.2.j)
- ☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ______ PHS Animal Welfare Assurance Number ______
- ☒ FUNDING MECHANISM Research - other than RAPID or EAGER
- ☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number ______ Exemption Subsection ______ or IRB App. Date ______
- ☐ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j) ______
- ☒ COLLABORATIVE STATUS A collaborative proposal from multiple organizations (GPG II.D.4.b)

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CERTIFICATION PAGE

Certification for Authorized Organizational Representative (or Equivalent) or Individual Applicant

By electronically signing and submit ing this proposal, the Authorized Organizational Representative (AOR) or Individual Applicant is: (1) cer ifying hat statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Fur her, the applicant is hereby providing certifications regarding conflict of interest (when applicable), drug-free workplace, debarment and suspension, lobbying activities (see below), nondiscrimination, flood hazard insurance (when applicable), responsible conduct of research, organiza ional support, Federal tax obligations, unpaid Federal tax liability, and criminal convictions as set forth in the NSF Proposal & Award Policies & Procedures Guide,Part I: the Grant Proposal Guide (GPG). Willful provision of false information in his applica ion and its supporting documents or in reports required under an ensuing award is a criminal offense (U.S. Code, Title 18, Sec ion 1001).

Certification Regarding Conflict of Interest

The AOR is required to complete certifications stating that he organization has implemented and is enforcing a written policy on conflicts of interest (COI), consistent wi h the provisions of AAG Chapter IV.A.; that, to he best of his/her knowledge, all financial disclosures required by the conflict of interest policy were made; and that conflicts of interest, if any, were, or prior to the organization's expenditure of any funds under he award, will be, satisfactorily managed, reduced or eliminated in accordance with the organiza ion's conflict of interest policy. Conflicts that cannot be satisfactorily managed, reduced or eliminated and research that proceeds without the imposition of conditions or restrictions when a conflict of interest exists, must be disclosed to NSF via use of the No ifications and Requests Module in FastLane.

Drug Free Work Place Certification

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent), is providing the Drug Free Work Place Certification contained in Exhibit II-3 of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Ye (b) (4) [redacted]

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) or Individual Applicant is providing the Debarment and Suspension Certification contained in Exhibit II-4 of the Grant Proposal Guide.

Certification Regarding Lobbying

This cer ification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for he United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned cer ifies, to the best of his or her knowledge and belief, that:
(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or coopera ive agreement.
(2) If any funds o her than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connec ion with his Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, "Disclosure of Lobbying Activities," in accordance with its instruc ions.
(3) The undersigned shall require that the language of this cer ification be included in the award documents for all subawards at all iers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This cer ification is a material representa ion of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Certification Regarding Nondiscrimination

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) is providing he Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Grant Proposal Guide.

Certification Regarding Flood Hazard Insurance

Two sec ions of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:
(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

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(1) for NSF grants for he construc ion of a building or facility, regardless of the dollar amount of the grant; and
(2) for o her NSF grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

Certification Regarding Responsible Conduct of Research (RCR)
(This certification is not applicable to proposals for conferences, symposia, and workshops.)

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative is certifying that, in accordance with the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.B., the ins itution has a plan in place to provide appropriate training and oversight in he responsible and ethical conduct of research to undergraduates, graduate students and postdoctoral researchers who will be supported by NSF to conduct research.
The AOR shall require that the language of this cer ification be included in any award documents for all subawards at all tiers.

CERTIFICATION PAGE - CONTINUED

Certification Regarding Organizational Support

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) is certifying that there is organizational support for the proposal as required by Section 526 of the America COMPETES Reauthoriza ion Act of 2010. This support extends to he portion of the proposal developed to sa isfy the Broader Impacts Review Criterion as well as the Intellectual Merit Review Criterion, and any additional review criteria specified in the solicitation. Organizational support will be made available, as described in the proposal, in order to address the broader impacts and intellectual merit activities to be undertaken.

Certification Regarding Federal Tax Obligations

When the proposal exceeds $5,000,000, the Authorized Organiza ional Representative (or equivalent) is required to complete the following cer ification regarding Federal tax obligations. By electronically signing the Certifica ion pages, he Authorized Organizational Representative is certifying that, to the best of their knowledge and belief, the proposing organiza ion:
(1) has filed all Federal tax returns required during the three years preceding this certifica ion;
(2) has not been convicted of a criminal offense under the Internal Revenue Code of 1986; and
(3) has not, more than 90 days prior to this certification, been notified of any unpaid Federal tax assessment for which the liability remains unsa isfied, unless the assessment is the subject of an installment agreement or offer in compromise hat has been approved by he Internal Revenue Service and is not in default, or the assessment is the subject of a non-frivolous administra ive or judicial proceeding.

Certification Regarding Unpaid Federal Tax Liability

When the proposing organization is a corporation, he Au horized Organiza ional Representative (or equivalent) is required to complete the following certification regarding Federal Tax Liability:

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) is certifying that the corporation has no unpaid Federal tax liability hat has been assessed, for which all judicial and administrative remedies have been exhausted or lapsed, and that is not being paid in a timely manner pursuant to an agreement with the au hority responsible for collecting he tax liability.

Certification Regarding Criminal Convictions

When the proposing organization is a corporation, he Au horized Organiza ional Representative (or equivalent) is required to complete the following certification regarding Criminal Convictions:

By electronically signing the Certifica ion Pages, the Authorized Organiza ional Representative (or equivalent) is certifying that the corporation has not been convicted of a felony criminal viola ion under any Federal law within the 24 months preceding the date on which the certification is signed.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME **Nancy S Daneau**	**Electronic Signature**	**Aug 7 2015 11:28AM**

TELEPHONE NUMBER	EMAIL ADDRESS	FAX NUMBER
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PROJECT SUMMARY

Overview:

Estimating the state of the body (e.g. position of the upper limb) through the integration of sensory cues ("multimodal state estimation") is a critical integrative function for most organisms. Although much is known about state estimation for the limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1)the multiple areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have been associated with both multisensory enhancement and suppression; 2)functional interactions among these areas have yet to be characterized;3)the relation between sensitivity to visual and somatic cues and computational theories of multisensory integration have been incompletely explored; 4)multimodal areas are thought to contribute to perceptual (body image) and action-based (body schema) representations, whose interactions at the neural and behavioral levels are not well understood. Here we will address these issues by quantifying changes in spiking, LFP activity and neural coherence within and between fronto-parietal areas of the monkey implicated in state estimation using virtual reaching tasks that alter the reliability and semantic information of visual cues. Aim 1 will characterize the local (areal) effects of varying visually-derived semantic information about upper limb structure. We predict that as semantic information becomes more complex (i.e. more visually arm-like), sites associated with representing body image, but not body schema, will show progressively larger effects of integration and sites involved in representing both body representations will show evidence of neural coupling. Aim 2 will characterize the local effects of changes in the relative reliability of visual and somatic position cues. We predict that as visual state information becomes more reliable, recording sites associated with representing the body schema, but not body image, will show progressively larger effects of integration; sites involved in representing both representations are again predicted to show evidence of neural coupling. Aim 3 will characterize changes in functional connectivity among multimodal cortical areas using data recorded in Aims 1 & 2. We predict that sites involved in body schema and/or body image will show strong evidence of functional connectivity; e.g. sites involved in representing primarily body image and body schema, respectively, will show progressively stronger correlations as semantic and visual state information increases. Moreover, these correlations are predicted to be stronger between sites with similar visual-somatic sensitivities.

Intellectual Merit :

State estimation and multimodal integration are currently topics of great interest due to their relevance for understanding perception, sensorimotor control and adaptation to neural prosthetic and sensory substitution devices. Although much is known about these functions at the behavioral level, their underlying neural mechanisms remain poorly understood in the cortex, particularly at the network level and during the control of action. This proposal will address key questions about the multimodal state estimation by characterizing activity within and across several areas of the cortex. The information gained from these studies will considerably advance our knowledge of multimodal integration, state estimation and sensorimotor control, particularly at the network level in the cortex.

Broader Impacts :

The research described here has significant potential to impact national needs in the consumer, healthcare, military, and industrial settings by advancing the fundamental engineering and neuroscience knowledge necessary to create the next generation of brain-machine interfaces. The broader impacts of this research will be addressed through educational activities designed to: (1)engage high school students underrepresented in STEM fields through continued development of hands-on instructional modules; (2)provide research opportunities for undergraduate students via existing internship mechanisms at ASU; (3)mentor students in the broader implications of scientific research through involvement in local and national organizations engaged in the ethical, societal, and policy implications of neuroscience research; and (4)engage the public in discussions on neuroscience, bioengineering and their interaction though public lectures and contributions to an interactive exhibit at the Arizona Science Center.

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TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.B.2.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.B.2.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Specific Aims (SA)

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment. The specific aims of the project are as follows:

SA1: Characterize the effect of varying semantic information about limb structure on oscillatory and spiking activity *within* multimodal cortical areas during arm state estimation

Cross-modal sensory stimuli are integrated not only for the formation of body schema, which is used for action, but also for the formation of the **body image**, which contributes to our sense of limb ownership. The latter in particular appears to be strongly influenced by semantic knowledge about how the body is structured. Here we will characterize the effects of varying such semantic knowledge on spiking, LFP activity, and local (areal) neural coherence across multimodal networks of the frontal and parietal lobes which display varying visual/somatic feedback sensitivities (PMv, area 5, and 7b). Monkeys will make reaching movements while receiving semantic information of varying complexity in different experimental blocks, ranging from an abstract arm endpoint stimulus (a sphere) to a fully rendered monkey avatar arm. Analysis will focus on a short, 1 second static holding period preceding reaching movements to virtual targets. We predict that as semantic information becomes more complex (i.e. more arm-like), reach reaction times will decrease and recording sites associated with representing the **body image** will show progressively larger effects of integration. More specifically, we predict that neural population responses, indexed by LFP power in the gamma band (which has been implicated in body-ownership) will be progressively enhanced and will be coherent with the spikes emitted by the cells that show enhanced spiking. Conversely, we predict that sites associated with representing the **body schema** will show minimal or no effects of semantic complexity. Instead, presentation of any visual stimulus will generally result in suppressed LFP power in the beta band (implicated in sensorimotor state) at these sites, which will be coherent with the spikes of cells that are suppressed. Lastly, sites involved in representing both body image and body schema are predicted to show evidence of cross frequency (beta-gamma) coupling. Changes in spiking and the direction of this change (enhancement/suppression) should reflect the strength of coupling at these sites.

SA2: Elucidate changes in oscillatory and spiking activity *within* multimodal cortical areas as a function of changes in the relative reliability of visual and somatic position cues

Psychophysical studies have demonstrated that sensory signals are optimally (or near optimally) integrated during both perceptual and action tasks in that they are weighted according to their relative reliabilities. Cortical correlates of optimal integration have been identified at the single cell and population levels during perceptual tasks but not during motor tasks and network level correlates of multimodal integration are poorly understood in general. As a result, in SA2 we will quantify changes in spiking, LFP activity, and local neural coherence in frontal and parietal areas as a function of the reliability of visual state (position) information. As in SA1 monkeys will make reaching movements to virtual targets and analysis will focus on the static holding period preceding the reach. Reliability of the visual information will be varied on a trial by trial basis by providing either a clear visual stimulus, one of two levels of a blurred visual stimulus, or no visual stimulus. We predict that as visual state information becomes more reliable, variability in limb positions will decrease and recording sites associated with representing the body schema will show progressively larger effects of integration. Specifically, we predict that LFP power in the beta band will be progressively suppressed and will be coherent with the spikes of cells that show suppressed spiking. Conversely, we predict that sites associated with representing the body image will show minimal or no effects of visual reliability. Instead, presentation of visual stimuli that recruited the body image in SA1 will generally result in enhanced LFP power in the gamma band , which will be coherent with the spikes of cells that are enhanced. Lastly, sites involved in representing both body image and body schema should again show evidence of cross frequency (beta-gamma) coupling and changes in spiking that reflect the strength of coupling.

SA3: Characterize changes in functional connectivity *among* multimodal cortical areas as a function of changes in semantic information and sensory reliability.

For this aim, no new experiments will be conducted. Instead this aim will focus on quantifying the degree of functional connectivity among sites in multimodal parietal and frontal areas. That is, we predict that sites involved in body schema and/or body image will show strong evidence of functional connectivity, assessed via inter-areal (long-range) neural coherence. More specifically, sites involved in body image will change show progressively stronger correlations as semantic information increases and sites involved in representing the body schema will show progressively stronger correlations as visual state information increases. However we hypothesize that changes in functional connectivity will be stronger between sites with similar visual-somatic sensitivities. That is, increasing the reliability or semantic information of visual signals should be associated with stronger changes in correlations between sites in strongly-moderately visual areas (PMv and 7b) than between areas that are strongly-moderately somatosensory (area 5 and 7b).

Rationale and Significance

Multimodal integration is currently a topic of great interest to both neuroscientists and engineers due to its relevance for understanding perception, the control of action, and adaptation to neural prosthetic and sensory substitution devices. Integration is thought to be necessary in part because sensory information is inherently noisy, which can lead to uncertainty in estimating the state of the environment and our own bodies, including the positions and velocities of our own limbs. Theoretical and behavioral studies have demonstrated that combining information from different senses through integration can improve state estimates. Moreover, several studies have shown that sensory signals are combined in a Bayes-optimal (or nearly optimal) manner, i.e. sensory inputs are weighted according to their relative reliabilities and combined with prior information to maximize the precision of state estimates (Ernst and Banks, 2002; Kording and Wolpert, 2004; Angelaki et al., 2009).

Despite the importance of multimodal integration for both perceptual and motor function, its neural mechanisms remain relatively poorly understood. Most of what is known comes from studies in monkeys of a subcortical structure, the superior colliculus (SC). For example, Stein and colleagues have shown that the spiking activity of neurons in the SC under bimodal conditions can be either enhanced or suppressed with respect to unimodal responses depending on such factors as the spatial and temporal congruency of the stimuli (Meredith and Stein, 1983, 1986b, a; Meredith et al., 1987; Meredith and Stein, 1996; Kadunce et al., 1997). Much less is known however about mechanisms of multimodal integration in the cortex. Work in monkeys has focused on integration of visual-vestibular (Bremmer et al., 2002; Angelaki et al., 2009), audio-visual (Ghazanfar et al., 2005; Sugihara et al., 2006; Lakatos et al., 2007; Chandrasekaran and Ghazanfar, 2009), visual-tactile (Zhou and Fuster, 2000; Avillac et al., 2007) and visual-proprioceptive (Graziano, 1999; Graziano et al., 2000; Shi et al., 2013) inputs. As in the SC, multimodal integration during these tasks is often associated with both enhancement and suppression of spiking activity, though suppression of spiking and spiking variability appears to be associated with greater encoded stimulus information in some areas (Kayser et al., 2010; Shi et al., 2013).

Studies directed at understanding multisensory integration in the formation and maintenance of representations of the body face some unique challenges. Body representations are essential for action, relating bodily signals to external space for planning and directing movements, and for agency, the feeling of control over one's actions (Tsakiris and Haggard, 2005). This requires the integration of visual, proprioceptive and tactile inputs, leading to a representation known as the body schema (Kammers et al., 2009a; de Vignemont, 2010; Newport et al., 2010). However, body representations are also essential for perception, i.e. for the sense of body ownership (aka self-attribution) and embodiment (Blanke, 2012). This also depends upon integration of visual, proprioceptive and tactile cues, as illustrated by the rubber hand illusion (RHI), resulting in the body image (Kammers et al., 2009a; de Vignemont, 2010; Newport et al., 2010). Although multisensory integration for body representations is generally thought to follow principles of Bayes optimality (Kording and Wolpert, 2004), each form of body representation is influenced by other factors as well. For example, visuo-proprioceptive integration is sensitive to the stage of action planning (Sober and Sabes, 2003), i.e. vision is weighted more during the computation of visually-derived movement vectors, while proprioception dominates the computation of joint based commands. Self-attribution on the other hand is sensitive to semantic knowledge about limb structure, i.e. the sense of body ownership is if such structure is violated, even if the visual cues are otherwise congruent (Tsakiris and Haggard, 2005; Blanke, 2012; Tieri et al., 2015). In addition to the these factors, a lack of understanding of critical neural factors, including functional heterogeneity of multisensory cortical areas, network level interactions, correspondence to prevailing computational theories of multisensory integration, as well as the dual nature of body representations in the brain, limit our understanding of multisensory integration for state estimation. These factors are discussed in detail below.

Heterogeneity of multisensory cortical areas.

Numerous areas have been implicated in state estimation for the limb including the primary motor, premotor, primary somatosensory, and posterior parietal cortices as well as basal ganglia and cerebellum (Brovelli et al., 2004; Mulliken et al., 2008; Taig et al., 2012). Many of these areas are also multimodal in nature, though their relative sensitivities to visual, tactile and proprioceptive inputs appear to vary considerably across areas. In monkeys, this has been studied most directly in association regions of the cerebral cortex, e.g. ventral premotor cortex (PMv), superior parietal lobule (area 5) and inferior parietal lobule (7b) (Fig. 1). Notably, PMv and area 5 are reciprocally connected to each other, as are 7b and area 5 (Neal et al., 1987; Cavada and Goldman-Rakic, 1989b). All three of these areas have been shown to be modulated both by somatically and visually derived limb position signals during perceptual tasks, with congruent bimodal cues generally being associated with enhancement of spiking activity (Graziano et al., 1994; Graziano, 1999; Graziano et al., 2000; Graziano et al., 2004). Although the inferior parietal lobule was one of the first of these regions to be implicated in multisensory processing and action (Mountcastle et al., 1975) , information on 7b responses during the performance of well-controlled limb movement tasks is scant. PMv appears to play a role in signaling the visually-perceived position of the limb, rather than its actual (somatically signaled) position, during the performance of ongoing movements (Schwartz et al., 2004); as a result this area may be preferentially involved in body representations based on visual signals. In area 5, a region known to receive strong somatic inputs, activity is also modulated during action however, in contrast to what is observed in perceptual tasks, visuo-proprioceptive integration during action manifests in suppressed spiking (Shi et al., 2013). Other factors undoubtedly play a role such in determining the effect of integration at the single cell level including the temporal synchrony of cues and their relation to ongoing oscillations (Perrodin et al., 2015), nevertheless these findings suggest that enhancement and suppression of spiking in multisensory areas depends on the nature of the task (perceptual vs. action), as well as the relative strength of relevant sensory inputs.

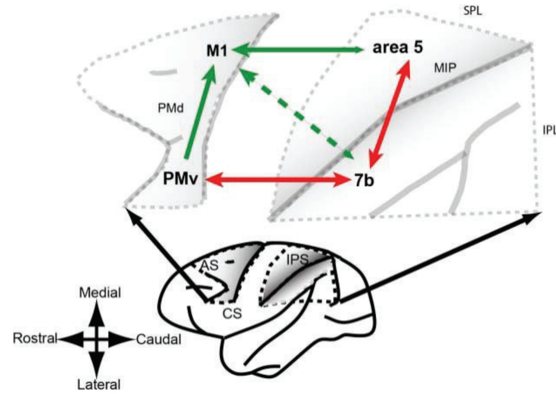

Fig. 1. Cortical network for multimodal limb state estimation. Red arrows indicate known anatomical connectivity that will be assessed functionally here. Green arrows: known anatomical (solid lines) and functional (dashed lines) connectivity with motor cortex (M1). AS: arcuate sulcus. CS: central sulcus. IPS: intraparietal sulcus.

Functional heterogeneity may extend to sites within anatomically defined areas. That is, cells at sites within a given multisensory area may have more in common with neurons in other “nodes” of the multimodal cortical network for state estimation, than with cells within their own anatomically defined regions. With regard to body representations, such “cell assemblies” could conceivably be devoted to largely perceptual functions, action-related functions or both (Buzsaki, 2010; Harris and Mrsic-Flogel, 2013). This could explain the observation that even in the same anatomical region (area 5), the effect of visuo-proprioceptive integration on spiking manifests differently (enhancement vs suppression) depending on whether the task recruits the body image or body schema (Graziano et al., 2000; Shi et al., 2013). In other words, these differences may be result from biased sampling of perceptual and action-related cell assemblies. Investigations of the neural mechanism of multimodal integration should take the possibility of such heterogeneities into account.

Network level Interactions

Although evidence for a state estimation network has previously been established, the effect of cross-modal interactions and their effects on inter-areal correlations have not been investigated. Most work examining network-level correlates of multimodal integration has been conducted in the context of audio-visual integration (facial and vocal signals in the monkey). Evidence for the latter comes from analyses of "neural coherence," a measure of the linear correlation between the frequency components of two neural signals. For example, presentation of combined auditory and visual signals has been shown to result in increased gamma band coherence between sites in the auditory cortex and the superior temporal sulcus, relative to unimodal conditions (Maier et al., 2008). Interestingly, no within area (local) changes in gamma band power were observed between unimodal and bimodal conditions, suggesting integration of vision and auditory signals was achieved through lateral interactions between these largely unimodal areas. More generally, these results and others suggest that inter-areal synchronization might underlie critical aspects of integration (Brovelli et al., 2004; Bauer, 2008; Senkowski et al., 2008; Engel and Fries, 2010; Siegel et al., 2012).

Optimal Integration

For the most part, neurophysiological investigations of multisensory integration remain largely disconnected from prevailing computational theories such as optimal integration. One noteworthy exception is the work of Angelaki who have demonstrated that non-human primates integrate visual-vestibular information in much the same way as humans and the mathematical rules by which this is performed are reflected in the responses of single neurons and small populations of neurons in multisensory cortex (Gu et al., 2008; Morgan et al., 2008; Angelaki et al., 2009). Recently, and more pertinent to the present proposal, Sabes and colleagues showed that monkeys could combine information about hand position, induced via multi–channel intracortical microstimulation (ICMS) to the somatosensory cortex, with vision to form an optimal, minimum–variance estimate of relative hand position (Dadarlat et al., 2015). Although this suggests that processes similar to optimal integration may underlie the integration of visuo-proprioceptive signals in the cortex, this has yet to be directly investigated at the single cell or network levels.

Image-Schema Interactions

The extent to which the perceptual (body image) and action-related (body schema) representations interact is controversial. Some psychophysical studies in unimpaired human subjects (mostly, but not exclusively using the RHI paradigm), suggests body image and body schema are largely dissociable (Kammers et al., 2009b), a view that has been challenged by others (Tsakiris et al., 2006; Newport et al., 2010). This inconsistency in interpretation is at least partly due to the fact that is very difficult to devise behavioral tasks that completely dissociate the body image and body schema (de Vignemont, 2010). In addition, as pointed out by Rognini, perceptual judgments and motor actions such as reaching appear to be characterized by somewhat different rules regarding multisensory integration, which makes comparing the results of such studies difficult (Rognini et al., 2013). Lastly, as suggested by de Vignemont, body image and body schema are likely interacting all the time, which is why disorders of body representations (such as asomatognosia) affect both perception and action (de Vignemont, 2010). Thus, rather than focusing exclusively on behavioral outputs, understanding the interaction of these representations could be strengthened by observing the consequences of these manipulations at the level of single neurons, small populations of neurons and networks of neurons believed to be involved in *both* types of body representations.

Studies of the neural correlates of body representations such areas have provided only limited insights. This may be due to the fact that these studies have examined activity in only perceptual or action tasks. For example, Graziano et al. (2001) showed that area 5 activity related to the felt position of the limb was *enhanced* by congruent visual information about limb structure and position (i.e. a fake monkey arm). However, activity in area 5 is also strongly related to arm position and arm movement (Georgopoulos et al., 1984; Lacquaniti et al., 1995; Buneo and Andersen, 2012). Moreover, somatically derived activity during the sustained maintenance of arm positions is also modulated by vision of the endpoint of the limb, though in this context activity is largely *suppressed* by vision (Shi et al., 2013). This suggests that even in the same anatomical area, the effect of visuo-proprioceptive integration on spiking manifests differently (enhancement vs suppression) depending on whether this integration recruits the body image or body schema. Since most real world tasks likely recruit both representations, it is unclear what effect integration would have on spiking more generally. An alternative to dissociating the representations would be to devise experimental manipulations which alter the relative strength of the two representations and observing the corresponding effects in multisensory areas.

Analyses of cortical oscillations and functional connectivity may be particularly useful in this regard. Beta band oscillations are evident in many action-related areas and have been hypothesized to play a role in state estimation (Engel and Fries, 2010). Thus, changes in beta oscillations associated with sensory integration could be a hallmark of the body schema representation. Although gamma oscillations are also associated with action (e.g. during the planning periods of memory guided tasks), they are typically typically temporally dissociated from beta oscillations and are thought to represent more cognitive variables. Interestingly, the rubber-hand illusion, an illusion of the body image, is associated with gamma modulation (Kanayama et al., 2007). This suggests that multimodal integration associated with body image and body schema might be identifiable in the gamma and beta bands, respectively of ongoing cortical oscillations. Moreover, interaction between the representations might be evident in the cross-frequency coupling (Canolty et al., 2006).

Conclusion

The research proposed here has significant potential to impact our understanding of such basic processes as multisensory integration, state estimation, and sensorimotor control while also advancing the fundamental engineering and neuroscience knowledge necessary to create the next generation of brain-machine interfaces, which are envisioned to incorporate artificial somatosensory feedback with vision (Bensmaia and Miller, 2014). The feasibility of such an approach has already been established using monkey models (Shokur et al., 2013; Dadarlat et al., 2015). Optimizing these systems will depend critically on understanding the mechanisms of integrations within and among the many multisensory brain areas, as well as understanding of how the body image and body schema interact as subjects learn to use and ultimately embody these devices. Current state-of-the-art robotic devices are not yet capable of real-time high dimensional, natural movements that are likely necessary for embodiment (Putrino et al., 2015). Even if such devices were currently available, other factors would likely make them impractical for patients to use without extensive training. Virtual devices however offer a safe and practical alternative to robotic ones, allowing a multitude of behaviors to be learned and trained (Bohil et al., 2011; Putrino et al., 2015). Precisely how realistic such environments need to be to enable embodiment is unclear; diverse virtual stimuli have been used in different studies, with no attempt to determine the optimal (or minimal) stimulus for enabling embodiment. The studies proposed here, which involve varying the degree of semantic information about limb structure, will provide critical information in this regard.

Hypotheses

The overarching hypothesis being addressed in this proposal is that network-level interactions (neural coherence (Schoffelen et al., 2005; Womelsdorf et al., 2007; Senkowski et al., 2008; Siegel et al., 2012)) among heterogeneous cortical areas drive changes in spiking activity across the network in a context-dependent manner, contributing to the coherent multimodal representation of limb state that is essential for perception and action. This overarching hypothesis, combined with 1) neuroanatomical evidence for a multimodal state estimation network (Muakkassa and Strick, 1979; Matelli et al., 1986; Neal et al., 1987; Cavada and Goldman-Rakic, 1989b, a; Tanne-Gariepy et al., 2002; Rozzi et al., 2006), 2) neurophysiological results from areas within this network (Graziano et al., 2000; Schwartz et al., 2004; Shi et al., 2013; Dadarlat et al., 2015), and 3) behavioral observations that multimodal integration for the limb depends on both the relative precision of relevant sensory inputs (van Beers et al., 2002; Kording and Wolpert, 2004) as well semantic information regarding limb structure (Tsakiris and Haggard, 2005; Tieri et al., 2015) leads to the following specific hypotheses:

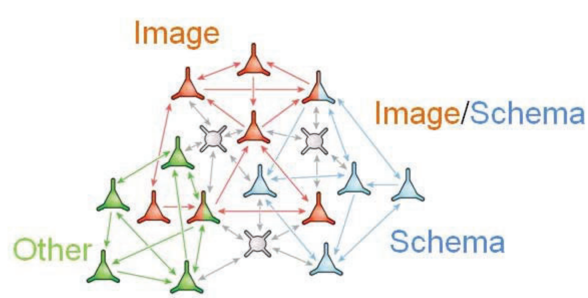

Fig. 2. Schematic representation illustrating interdigitated and partially overlapping cortical subnetworks for body image, body schema, and other (e.g. motor) representations. Adapted from Harris et al (2013).

1558151

1) We hypothesize that distinct sites across the cortical state estimation network will show strong effects of varying semantic information about limb position, implicating them in the multimodal representation of body image. More specifically, we predict that as semantic information becomes more complex (i.e. more arm-like), reach reaction times will decrease and sites associated with body image will show progressively larger degrees of LFP power enhancement in the gamma band, which will be locally coherent with the spikes of cells that show enhanced spiking. These hypotheses are based on observations that manipulations of the body image are associated with altered reaction times (Spence et al., 2004) and gamma modulation (Kanayama et al., 2007) in humans and enhanced spiking in monkeys (Graziano et al., 2000). Other sites are predicted to show minimal of no effects of semantic complexity but will instead be associated with a general suppression of LFP power in the beta band, which will be coherent with the spikes of cells that are suppressed (Hagan et al., 2012). These cells will be presumed to play a stronger role in the representation of body schema. Lastly, we expect that some sites will be associated with both body image and body schema; these sites are predicted to show evidence of cross frequency (beta-gamma) coupling. Changes in spiking and the direction of this change (enhancement/suppression) should reflect the degree of coupling at these sites.

2) Similarly, we hypothesize that distinct sites across the cortical state estimation network will show strong effects of varying visual limb state reliability, implicating them in the multimodal representation of body schema. Specifically, we predict that as visual state information becomes more reliable, variability in limb positions will decrease and sites associated with body schema will show progressively larger degrees of LFP power suppression in the beta band, which will be locally coherent with the spikes of cells that show suppressed spiking. This hypothesis is based on observations that suppression has been shown to be associated with greater encoded stimulus information in multisensory areas, and with greater limb position decoding accuracy in area 5 (Kayser et al., 2010; Shi et al., 2013). Other sites are expected to show minimal or no effects of increasing visual reliability but will instead be associated with a general enhancement of LFP power in the gamma band (for limb stimuli that recruited the body image in SA1), which will be coherent with the spikes of cells that are enhanced. Lastly, sites involved in representing both body image and body schema should again show evidence of cross frequency (beta-gamma) coupling with changes in spiking that reflect the strength of that coupling.

3) Lastly, we hypothesize that sites identified as being related primarily to body image or body schema will show strong evidence of functional connectivity with corresponding sites in other nodes of the cortical network for state estimation, assessed via inter-areal (long-range) neural coherence. That is, sites implicated in the body image representation will change show progressively stronger degrees of gamma coherence as semantic information increases; similarly sites involved in representing the body schema will show progressively stronger degrees of beta coherence as visual state information increases. However, changes in functional connectivity may be stronger between sites with similar visual-somatic sensitivities. That is, increasing the visual reliability or semantic information may be associated with stronger changes in coherence between sites in strongly-moderately visual areas (PMv and 7b) than between areas that are strongly-moderately somatosensory (area 5 and 7b).

Experimental Plan

All data will be collected in the PI's (Buneo) lab at ASU. Data analysis will be shared between members of the PIs lab and the Co-I (Pesaran) at NYU.

Apparatus

Rhesus monkeys will be trained to make arm movements within a semi-immersive, 3D virtual environment (Schwartz et al., 2004; Shi et al., 2013). Vision of an animal's real arm will be blocked by a barrier, but a virtual representation of the arm will be displayed on a 3D monitor that projects onto a mirror embedded in the barrier (Fig. 3). Arm movements will be monitored using retro-reflective marker based motion tracking system (Motion Analysis Inc.) and eye movements will be monitored using a remote optical eye tracking system (Applied Science Laboratories, Inc.). Neural activity will be recorded extracellularly using implanted fixed microelectrode arrays (Blackrock Microsystems, Inc.). Funds have been requested to purchase a

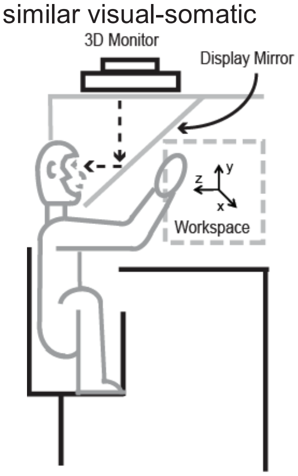

Fig. 3. Vision of the animal's real arm will be blocked by a mirror, but a virtual representation will be displayed on a 3D monitor that projects onto the mirror.

1558151

288 channel Omniplex Data Acquistion system (Plexon, Inc.) which will allow recording from 3 96-channel arrays simultaneously including spikes and fields. Single spikes will be isolated from the amplified and filtered (600-6000 Hz) signal via a time-amplitude window discriminator and sampled at 2.5 kHz. Local field potentials will also be isolated from the amplified signal using a band-pass filter of 2-300 Hz and digitized at 1000 Hz.

Virtual Reality System

(b) (4) [redacted] Motion capture is used to allow the virtual limb to be controlled using kinematic data. In order to calculate joint angles from marker location, a complete upper limb kinematic model of a rhesus macaque upper limb is developed by first generating an anatomically correct skeletal model of the macaque upper limb using MRI images of the arm, hand and shoulder. Once the bones are rendered, they are imported into SIMM (Musculographics, Inc.), to calculate joint angles from recorded marker positions. To ensure that the virtual limb moves in a realistic manner, the joints are constrained by anatomically correct kinematic models of all the joints in the macaque upper limb. These can be customized for individual animals to adjust for large differences in subject-specific anatomy. When motion capture data is input into SIMM, marker position is converted to joint angle data using the SIMM kinematic model. A 'segmental model' is also generated, which generates a skeletal pose for each frame of data based on marker location. During online solving, segment position is streamed into Vizard (Worldviz, Inc.) to drive the upper limb avatar.

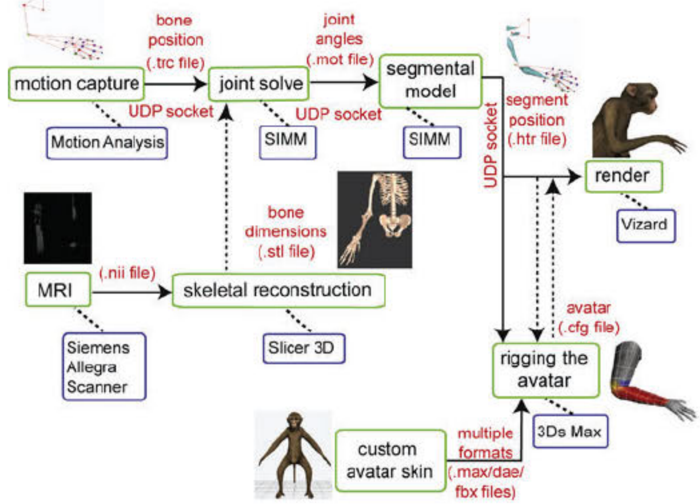

Fig. 4. Software and hardware pipelines that will be used to produce avatar rendering and motion from kinematic data in real-time. Solid arrows denote data streamed in real-time, while dashed arrows denote files that are statically loaded into the appropriate programs.

For animating the virtual arm, a macaque mesh is designed in 3Ds Max (Autodesk,San Francisco, CA). Avatar meshes that are compatible with 3DsMax are covered in thousands of vertices that can be programmed to move in synergy with the kinematic model in order to give the appearance of natural movement. Once the avatar is completed, it is exported from3Ds Max to Vizard. During behavioral experiments, the upper limb avatar renderer in Vizard receives "movement instructions" via a Motion Analysis "Software Developer Kit 2" (SDK2) interface, and a customized SDK2 client for Vizard. The coordinates of the segmental data information are sent to Vizard via a User Datagram Protocol (UDP) socket connection. Figure 4 presents a system diagram of the components required to generate the real-time, movements of the virtual limb.

Experimental Design and Data Analysis

***SA1* will characterize the effect of varying semantic information about limb structure on oscillatory and spiking activity *within* multimodal cortical areas during arm state.**

Behavioral Paradigm

Animals will perform a reaction-time task involving 2 consecutive combined eye and arm movements. The first combination will involve movements from a single (central) starting position to one of eight targets arranged in a frontal plane followed by a saccadic eye movement back to the central starting position. The virtual limb stimulus will be visible at the beginning of each trial as well as during the initial portion of the movement toward the target but will be extinguished approximately halfway through the movement. Once the peripheral arm endpoint and central fixation positions have been acquired a 'static holding period' will commence where animals will be required to continue fixating the center of the display (+/- 5°) while maintaining their arm position at the target at the periphery for a period of randomized period of 1000-2000 ms. During this static holding period, the virtual limb stimulus will be returned on half of the trials (Vision (V) Condition) but will not be returned on the remaining trials (No-Vision (NV) Condition). At the end of the holding period another target will be cued at one of four pseudorandomly chosen positions arranged around the holding position, requiring the animal to make a second reaction-time reach. The purpose of this second reach is to ensure (as much as possible) that activity during the static holding position is positional and not related to a default plan to move back to a predictable position (the starting position). A minimum of 20 reaches to each of the eight initial targets will be performed; which will involve 5 movements to each the four secondary targets. Analysis of neural data will focus primarily on the last 1000 ms of the static holding period preceding movements to the second target. Reaction times associated with these second reaches will be quantified.

To examine the effect of semantic knowledge of limb structure, a different virtual arm stimulus will be used in each of 4 blocks of trials. Although such information can vary many ways including shape, texture, and color, in these initial studies we will primarily examine the effect of body discontinuity. Such discontinuities have recently been shown to significantly reduce feelings of perceived body ownership in humans(Tieri et al., 2015). Figure 5 shows an example of the manipulations used by Tieri and colleagues, applied to a human avatar. For the experiments proposed here we intend to look examine four virtual limb stimuli consisting of 1) a simple sphere (as employed by Shi et al. 2013), 2) a macaque monkey hand, 3) a macaque lower arm (hand, wrist and forearm), and 4) a full macaque arm (hand, wrist, forearm and upper arm). Note that stimuli 1 and 2 have the degree of body discontinuity but differ with respect to other factors such color, texture etc. However, both conditions are necessary for relating the present results to previous results from the PIs lab, which used a sphere. Stimuli 2-4 differ mainly with respect to body discontinuity.

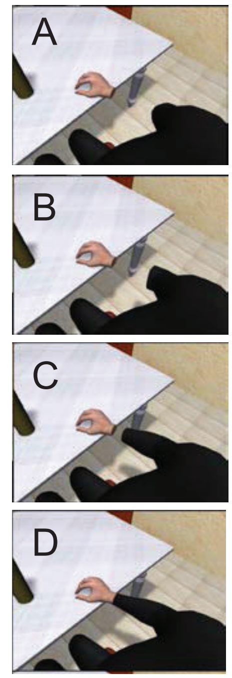

Fig. 5. Manipulations of body discontinuity in a human avatar (Tieri et al (2015)). A: missing upper and lower arm. B: missing lower arm. C: missing wrist. D: full arm.

Analysis of Neurophysiological Data

All analyses will be conducted using custom Matlab® code developed in the PI or Co-Is lab or with the Chronux software package (Bokil et al., 2010).

Spike Data Analyses

Effects of the visual conditions (semantic information) on spiking will be assessed using standard indices of response enhancement/suppression. The first will compare the response of a neuron in a given visual condition (V), with the maximal response in the no-vision condition (NV) (Meredith and Stein, 1986b):

$$INDX_1 = \left[\left(V_{pnv} \quad NV_{pnv}\right)/NV_{pnv}\right] \times 100 \qquad (1)$$

where NV_{pnv} represents the mean firing rate at the preferred position in the NV condition and V_{pnv} represents the corresponding rate in the V condition. To account for the possibility that some enhancement/suppression might arise from differences in tuning between conditions, we will also calculate an index that is based on the preferred position in each condition (as opposed to $INDX_1$, which is based purely on the preferred position in the NV condition):

$$INDX_2 = \left[\left(V_{pv} \quad NV_{pnv}\right)/NV_{pnv}\right] \times 100 \qquad (2)$$

Effects of differing semantic information on these indices will be assessed by first forming distributions of indices for each condition by bootstrapping across trials then calculating the slope of the relation between index and semantic information. Figure 6 illustrates the possible results of this procedure for five idealized sites. Based on previous studies (Graziano et al., 2000), sites associated primarily with body image are predicted to show enhanced spiking in the presence of the virtual limb. The extent of this enhancement should increase with increasing semantic information (indicated by the slope of the “image” plot) but this effect may be reduced for sites also influenced by body schema (“image-schema”), which is predicted to suppress spiking in the presence of the virtual limb (Shi et al., 2013). For similar reasons, sites primarily associated with body schema will generally be suppressed and not show trends with increasing semantic information (“schema”) though some sites may also be influenced by body image and show trends with semantic information but remain suppressed overall (“schema-image”). Thus, recording sites in each area will be classified as ‘image’ sites, ‘schema’ sites, ‘image-schema’,

1558151

'schema-image' or not multimodal, based on their spiking activity. These "site classifications" will be used to group sites together for further within area and inter-areal analyses.

We will also assess changes in across-trial spiking variability using the Fano factor (FF), which is computed from the slope of the relation between spike count variance and spike count mean. Fano factors will be computed for all sites in a given area as well as for sites of a given classification and will be compared across conditions using a similar procedure as described above for the indices. Intra-trial variability will also be quantified using the square of the coefficient of variation (CV^2) of the interspike intervals (Nawrot et al., 2008). The CV^2 will also be calculated for all sites in a given area as well as within sites of a given classification; differences across visual conditions will be assessed the Kruskal-Wallis test using an alpha of 0.05.

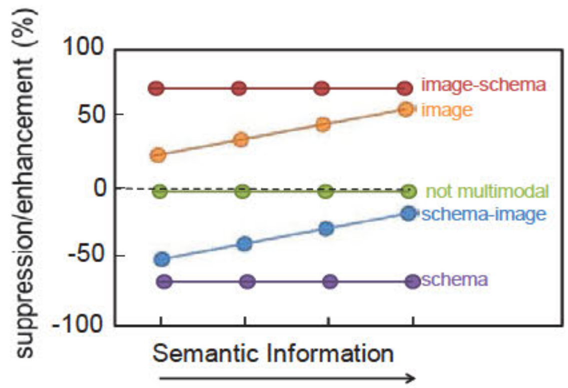

Fig. 6. Predicted changes in suppression / enhancement as a function of semantic information about limb structure for sites involved in representing primarily body image, body schema or varying degrees of both representations.

A decoding algorithm will also be used to assess how well population activity can predict position in the presence and absence of limb vision; this will done for all visual semantic conditions. Activity will be used as input to a maximum-likelihood classifier that will predict the position of the limb on a given trial given the neural population activity on that trial (Pouget et al., 2000). The percentages of correctly and incorrectly classified trials will then be represented graphically as confusion matrices (Scherberger et al., 2005). Differences in decoding performance across visual conditions will be assessed using the Kruskal-Wallis test using an alpha of 0.05.

LFP Spectrum, Spike-field Coherence (SFC), and Cross-frequency Coupling Analyses

For each LFP recording, we will calculate the spectrum, using multitaper methods with a +/- 250 ms analysis window, stepped 50 ms between windows with +/- 2.5 Hz smoothing, and aligned either to the acquisition of the first endpoint position or start of the reach to the second endpoint position (Mitra and Pesaran, 1999). We will test for differences in LFP power at each frequency (1-100 Hz) and among visual conditions using the Kruskal-Wallis test ($p<0.05$). This will be done without regard to site classification, as changes in LFP power may occur independently of changes in spiking. In addition, we will characterize the LFP power for all sites with the same classification and calculate the percentage of LFPs that showed a significant difference in power among conditions at a given frequency..

For each spike-field recording, we will calculate the SFC using multitaper methods with a +/- 250 ms analysis window, stepped 50 ms between windows with +/- 5 Hz smoothing aligned either to the acquisition of the first endpoint position or start of the reach to the second endpoint position. To assess relationships between observed changes in LFP power and changes in spiking, the SFC will be calculated at all sites of a given classification. Note that because SFC is influenced by spiking activity recorded on the same electrode as LFP activity (Zanos et al., 2011), we will restrict our analyses of the local (with area) SFC to data recorded on neighboring electrodes. Assessments of differences in coherence across site classifications, will facilitated by calculating the z score for the estimated coherence (Jarvis and Mitra, 2001). Lastly, for sites classified as image-schema of schema-image, we will look for evidence of cross-frequency coupling using methods described by Canolty et al and Tort(Canolty et al., 2006) et al (Tort et al., 2010).

Reaction time analyses

For each limb position, differences in reaction times between the V and NV conditions will be assessed using the Wilcoxon rank-sum test (alpha = 0.05). We hypothesize that increasing semantic complexity reflects increasing congruency of visual and somatic information about limb position and therefore predict that reaction times will increase accordingly among the different visual conditions.

***SA2* will elucidate changes in oscillatory and spiking activity *within* multimodal cortical areas as a function of changes in the relative reliability of visual and somatic position cues.**

Behavioral Paradigm

A similar behavioral paradigm will be employed as in SA1. Animals will again perform a reaction-time task involving 2 consecutive combined eye and arm movements. Within each of 4 blocks of trials, animals will receive either a virtual limb stimulus (V condition) or no visual stimulus (NV condition) after completing the first of the 2 consecutive reaches. To examine the effect of visual reliability, we will manipulate the level of blurring of the virtual arm stimulus across blocks (Kording and Wolpert, 2004), from maximal blurring to no blurring, i.e. a clear stimulus. In addition, to explore the interaction between body image and body schema representations, each sequence of four blocks will be repeated in a given session using as many of the stimuli used in SA1 as possible (determined by the animal's performance level).

Analysis of Neurophysiological Data

We will use a similar approach to analyzing our neural data as in SA1, focusing on changes in spiking activity, LFP activity, SFC, and cross frequency coupling with changes in visual reliability. Figure 7 illustrates the possible effect of visual reliability manipulations for five idealized sites. Sites associated primarily with body schema are predicted to show suppressed spiking in the presence of the virtual limb. The extent of this suppression should increase with increasing semantic information (indicated by the slope of the "schema" line) but this effect may be reduced for sites also influenced by body image ("schema-image"), which is predicted to enhance spiking in the presence of the virtual limb. For similar reasons, sites primarily associated with body image will generally show enhanced spiking (for stimuli that recruited the body image in SA1) and not show trends with increasing visual reliability ("image") though some sites may also be influenced by body schema and show trends with visual reliability but remain enhanced overall ("image-schema"). As in SA1, these "site classifications" will be used to group sites together for within area and inter-areal analyses, which will take a similar form to SA1.

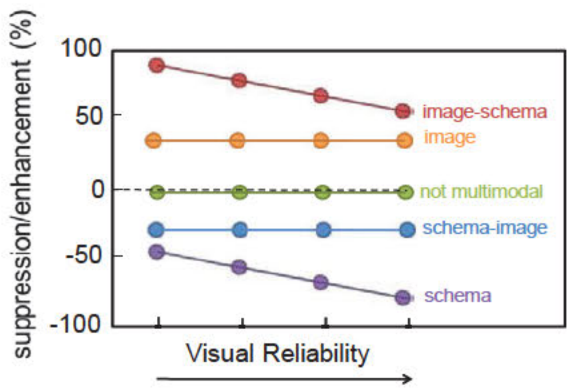

Fig. 7. Predicted changes in suppression / enhancement as a function of visual reliability for sites involved in representing primarily body image, body schema or varying degrees of both representations.

Analysis of Limb Position and Reaction Times

All statistical analyses will be conducted on position data recorded during the static holding period and using significance levels of 0.05. For each limb position, differences in mean wrist position between the V and NV conditions will be assessed using a MANOVA. Differences in position along the horizontal (x), vertical (y) and depth (z) axes between visual conditions will be assessed using the Wilcoxon signed-rank test. Variability in position along the horizontal (x), vertical (y) and depth (z) axes will be compared between visual conditions using Levene's test. We expect that the increasing levels of visual reliability will be associated with decreasing levels of variability in limb position along one or more axes, but with no change in mean position. This should also be reflected in the initial trajectories to the second target and we will look for such changes as additional evidence that state estimation has been affected by our manipulations. We will also quantify reaction times as in SA1, as modulations of the LFP beta band have been shown to be correlated with reaction time changes.

***SA3* *will* characterize changes in functional connectivity *among* multimodal cortical areas as a function of changes in semantic information and sensory reliability.**

For this aim, no new experiments will be conducted. Instead this aim will focus on quantifying the degree of functional connectivity among sites with similar classifications (as determined in SA1 and SA2)

1558131

but belonging to different anatomically-defined areas. This will be accomplished using similar SFC methods as those described above for SA1 and SA2.

Potential Problems and Limitations etc. (All Aims)

We have already shown that neurons in area 5 and 7b (see Preliminary data below) are modulated by the presence of a visual stimulus during the static holding period following a reach so we are confident that we will see similar changes here. It is possible however that we will not see not see widespread LFP or coherence changes locally that are consistent with our hypotheses in SA1 and SA2. This seems unlikely given previous results and preliminary analyses in area 5, but if spikes in a given area are coherent with fields at more distant sites, this will suggest that multimodal integration in some areas is facilitated by long-range rather than purely local interactions. Such interactions should be evident from analyses conducted in SA3.

We have anticipated seeing modulations in gamma band power due to manipulations of body image and modulations of beta band power due to manipulations of visual state information. The possibility of finding modulations of LFP power in the beta band in our tasks is high, given previous results from our lab and others. Regarding the proposed gamma oscillations during body image manipulations, we consider it likely but this is based largely on the results of a single paper in humans (Kanayama et al., 2007). As a result we will look for differences in other frequency ranges as well, including those in the theta and alpha bands, which have been shown to be coupled to gamma band oscillations in other contexts (Canolty et al., 2006). Such modulations might be expected to be more evident in other cortical layers than those targeted here, which are presumably deeper layers (van Kerkoerle et al., 2014). If modulations in alpha and beta are found it would suggest a future line of inquiry focused on laminar interactions among sites.

Due to the nature of the work, animals necessarily require extensive training to successively perform the tasks at a high level. As a result it is always unclear the extent to which the observed results are a reflection of an 'overtrained' condition or more general state of affairs and the current experiments will not allow us to distinguish between these possibilities. However, the use of chronic microelectrode recording arrays will allow us to track neural performance over many days and document any neural changes due fluctuations in behavioral performance. In addition, once this paradigm is established, it will allow future studies of adaptation to novel virtual visual and mechanical manipulations, as well as novel somatosensory inputs delivered via peripheral or intracranial stimulation. Such studies will provide additional critical information for the development of BMIs.

It has recently been proposed that a combination of two canonical operations, divisive normalization and phase resetting, can explain the flexible integration of multisensory information in a variety of systems and behavioral contexts (van Atteveldt et al., 2014). The present experiments are not designed to directly probe the role of such mechanisms in the multimodal integration for limb state estimation. However, we will look for signatures of these operations in our data, and interpret our results in the context of work in this area.

Proposed Use of Vertebrate Animals

We will use a maximum of 6 rhesus macaques, Macaca mulatta, for the experiments outlined in this proposal. Animals in the 3-5 kg range obtained from AAALAC approved primate centers will be housed in an AAALAC approved vivarium, and all of the research described in this plan will be carried out in AAALAC accredited facilities. All of the procedures described here have been approved by the Arizona State University (ASU) Institutional Animal Care and Use Committee, will be carried out in consultation with the University Veterinarian, and follow the guidelines established in the NIH Guide for the Care and Use of Laboratory Animals.

Justification for species and numbers: The primary reason we have chosen macaques is that the somatomotor cortex in these primates has been well studied and is known to be similar in structure and physiology to analogous cortical regions in humans. The rhesus macaque has served as an important model of neuroprosthetic control, and provided insights that have led directly to implementation in human subjects. Macaques have also been a significant model in the study of arm movements, and we plan to use arm movements as the main behavioral output in our studies. We generally are confident to write papers following experiments in two to three separate animals. This allows us some assurance that we have provided adequate data to counter both animal-to-animal and experiment-to-experiment variability. Thus, we are planning to use 6 animals, and have budgeted for that number. We emphasize that 6 primates is an absolute maximum, and anticipate further refinement of our methods will increase the amount and quality of data obtained from each animal. Lastly, we continually undertake literature searches with a key to identifying alternative means for pursuing our research aims. For example, a recent search (8/1/15) on Pubmed with the terms "multisensory integration" AND "monkey" AND "arm" produced 9 publications, but none of these was a neurophysiological investigation of interactions at the network level, as proposed here.

Methods for limiting comfort and distress: We have a fixed analgesia scheme defined by a standard institutional guideline. About a half hour prior to surgery, animals are dosed with oxymorphone (0.15 mg/kg) and meloxicam (0.2 mg/kg). Following surgery, animals are dosed again with oxymorphone (0.07-0.15 mg/kg) every 6-8 hours for 24 hours and meloxicam (0.1 mg/kg) every 24 hours for 72 hours. At the discretion of the DVM, a local anesthetic such as bupivicaine ID may be applied along the surgical margins. In the case of minor surgeries, the oxymorphone is replaced with buprenorphine (0.01-0.03 mg/kg).

Our animals are also monitored on a daily basis for signs of excess dehydration. The primary symptoms we guard for are lethargy and skin tenting. This combined with weekly weighings of the animals provides good monitoring for excess distress relative to water-restricted diets. In natural circumstances, these animals are well adapted to intermittent water access, and so they typically respond very well to controlled access (Toth and Gardiner, 2000). To insure health, the animals receive supplemental fruits and vegetables in their diet. We have not had any health crises at this facility resulting from watering schedules.

Finally, our animals are typically restrained in small primate chairs for 3 to 5 hours per day. This includes 2-4 hours with the head restrained. The animals do not show distress during these intervals. The animals all wear solid collars, and are transported to and from their cages using handling poles. We slowly acclimate the animals to each of the components of this process over the course of several days or weeks. This includes exposure to the animal handlers, the apparatus, and the experimenters combined with small rewards consisting normally of dried fruit. By the time the animals are trained and ready for implantation, they will normally come quietly out of their cages and position themselves into the primate chairs. As they are prepared for the experiments, the animals normally sit quietly in the chair, allowing the experimenter to affix their heads, attach recording leads to connectors, and attach motion tracking markers to their arms.

Occasionally the animals are subject to more direct handling than is normally the case. This is true for example during occasional control studies, or when we use ICMS to assess the sites of electrode placements. If the animals show signs of distress, we provide the animals with a light dose of acepromazine to serve as a tranquilizing agent.

Preliminary Data

As part of his CAREER award, the Co-I (Pesaran) has been studying excitatory and inhibitory interactions between eye and arm related regions of the posterior parietal cortex. He has recently found that the activity of a population of cells in LIP is suppressed when combined saccades and reaching movements are performed, compared to when saccade are made alone (Fig. 8), reminiscent of the cross-modal suppression of spiking that has been observed in other brain areas and tasks. Interestingly, this suppression is also reflected in the simultaneously recorded LFPs and corresponding spike field coherence. That is, LFP power in the beta band is also suppressed when combined reaches and saccades are performed (C), relative to saccades alone (B), and is coherent with the spiking activity of cells that are suppressed (D, red curve). Similar mechanisms could underlie the relation between

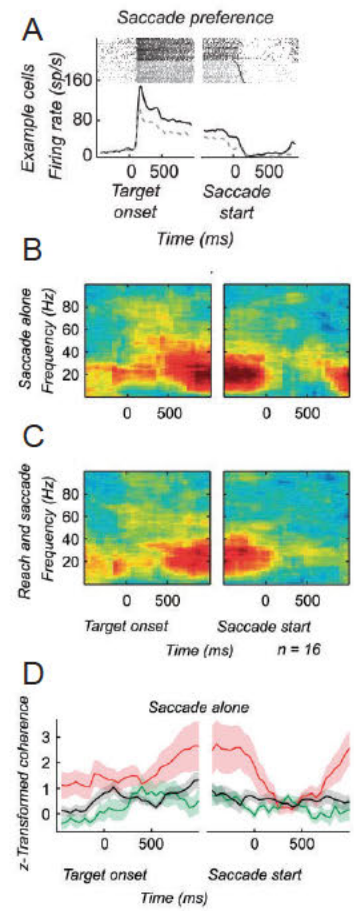

Fig. 8. Suppression of spiking activity (A) and LFP activity (B,C) for combined reaches and saccades, compared to saccades alone in LIP. D: Coherence between LFPs and spikes for cells with suppressed spiking.

spiking suppression/enhancement and cross-modal stimulation in multisensory areas, a hypothesis which will be tested directly in the present proposal.

As part of his CAREER award, the PI (Buneo), has been characterizing the mechanisms of integration of somatic (proprioceptive and efference copy) and visually-based limb position signals in the superior parietal lobule (SPL) and inferior parietal lobule (IPL). We initially examined visual-proprioceptive integration in parietal area 5 (SPL) of the monkey during the active maintenance of arm positions following reaches made with and without vision. We found that vision of the arm decreased neuronal spiking (Fig. 9A) and spiking variability and was also associated with improved decoding of arm position at the population level (Shi et al., 2013). These findings are consistent with those of Kayser et al. (2010) which showed that decreased spike rates and spiking variability under multimodal (audio-visual) conditions led to greater encoded stimulus information (Kayser et al., 2010). Local field potentials at corresponding sites also demonstrated significant spectral power in the beta band and at lower frequencies and preliminary analyses suggest this LFP power is suppressed in the presence of vision (Fig. 9C,D). More recently we have examined the responses of neurons in area 7b (IPL) during the same task (in one one of the same animals), using chronically-implanted microelectrode arrays. Thus far, results have been similar to what was found in the SPL; during the sustained maintenance of limb positions, vision of the arm was largely associated with suppression of spiking (Fig. 9B).

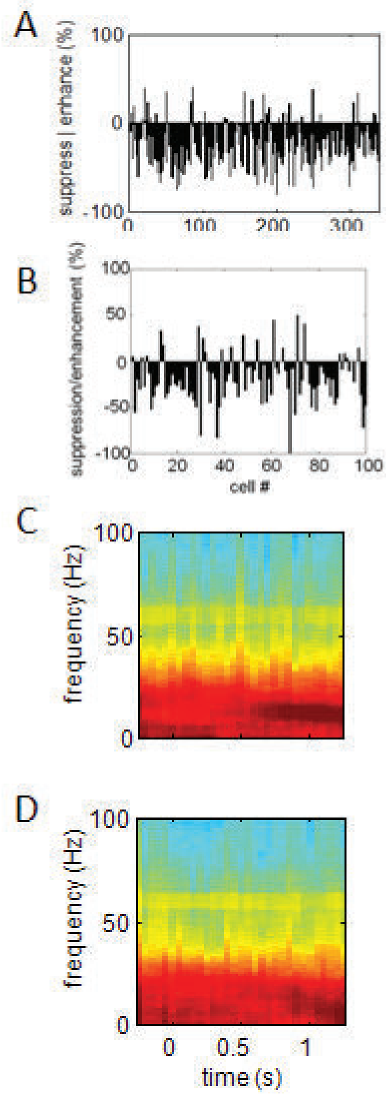

Fig. 9. Suppression/enhancement indices for area 5 neurons (A; N=338) and 7b neurons (B; N=100). Also shown are LFP spectrograms from a single area 5 site illustrating suppression in the beta band during the holding period (0.4-1.2 s) following a reach in the vision condition (D), compared to no-vision condition (C).

<u>Broader Impacts of the Proposed Work</u>

The PI has established labs that attract excellent students from multiple programs including biomedical engineering, psychology, and neuroscience, creating a culture of diversity and promoting interdisciplinary collaboration. The PI actively recruits undergraduate interns from the ASU Fulton Undergraduate Research Initiative (FURI) and School of Life Sciences Undergraduate Research (SOLUR) program, which provide funds for students to gain research experience in parallel with coursework. To date the PI's mentees have included female students, high school students, and students pursuing honors undergraduate theses. The PI has multidisciplinary affiliations that extend beyond his home department to enable interdisciplinary collaborations and training of students, and broad impact of the research results. Graduate Faculty affiliations external to the PI's home department currently include Neuroscience, Electrical Engineering, Mechanical Engineering, Arts Media and Engineering, and Kinesiology.

This project will also take advantage of numerous outreach and research opportunities offered at ASU. The PI will recruit undergraduates, including underrepresented students, for research subprojects from the ASU FURI and Solur programs and Barrett Honors College. Students of all levels will be trained in Responsible Conduct of Research, Institutional Review Board policies, and the Care and Use of Laboratory Animals, as appropriate to their research subprojects. Graduate students will have the opportunity to mentor undergraduate student research projects.

The proposed educational goals will draw upon neuroscience and engineering expertise to 1) engage high school students underrepresented in STEM fields through continued development of hands-on instructional modules; (2) provide research opportunities for undergraduate students via existing internship mechanisms at ASU; (3) mentor students in the broader implications of scientific research through involvement in local and national organizations engaged in the ethical, societal, and policy implications of neuroscience research; and (4) engage the public in discussions on neuroscience, bioengineering and their interaction though public lectures and contributions to an interactive exhibit at the Arizona Science Center.

Educ. Goal 1: Continued development instructional modules for high school students.

The PI and his students will develop hands-on instructional modules that enable high school students to learn about virtual reality and human-robot systems and the brain. The modules will be designed to complement and integrate seamlessly with existing Arizona Science Standards as articulated by the Arizona Department of Education. The PI will integrate these modules into the high school outreach program that he has developed as part of his previous NSF CAREER Award. The outreach infrastructure for the CAREER Award will be leveraged here, but the educational objectives in the proposed work will be expanded from systems neuroscience to include virtual reality and human-robot systems and will therefore enhance the outreach offerings. The instructional modules are currently being developed for the Project Lead the Way certified Biomedical Program at Campo Verde High in the local Gilbert Unified School District, but may be expanded to include Desert Ridge High, which has a similar program in Engineering. Supporting documents and instructions for the hands-on activities will be posted on the PI's webpage along with links to other learning resources to enable long-term sustainment of the program. The modules will also be contributed as a free collection to the NSF National Science Digital Library which provides high quality resources for innovative K-16 STEM education and provides free web-based searches of resources. Instructional videos will also be posted to ASU's "Science is Fun" video repository for public access.

Educ. Goal 2: Promote interdisciplinary undergraduate research opportunities via internships.

The PI will leverage existing institutional programs that fund undergraduate research through popular, competitive programs. Undergraduate students will be recruited through the ASU FURI and Barrett Honors College programs to conduct research on proposed topics. Students selected for FURI awards are required to meet regularly with their research advisors, submit written reports on research progress, and present their work at a poster symposium at the end of each semester. In addition to regular meetings and reports, Barrett Honors students are required to write an archival thesis, orally defend the thesis, and get approval from a two-member faculty committee in order to graduate with Honors. The PI has a strong track record of recruiting undergraduate students from these programs and mentoring them in skills such as Responsible Conduct of Research, networking, scientific writing, and scientific presentation. In addition, the topic of the proposed work lends itself to interdisciplinary discussions of neurophysiology, multisensory integration, and human-machine interfaces. Undergraduate student interns will participate in the design of experiments, data collection, analysis, and interpretation.

Educ. Goal 3: Enhance training and learning through exposure to local and national organizations engaged in the ethical, societal, and policy implications of neuroscience research

Graduate and undergraduate students that are associated with this project will be required to participate in regular colloquia organized in conjunction with students in the BioScience Ethics, Policy, and Law Program and the Human and Social Dimensions of Science and Technology Program. Graduate students will also be invited to join the PhD Plus Program, offered through The Consortium for Science, Policy & Outcomes (CSPO) and the Center for Nanotechnology in Society at ASU, which fosters the development of citizen scientists: with appropriate supervision, students integrate ethical, societal, or political considerations into their own scientific research, either by writing an additional dissertation chapter or undertaking another writing or research project. Students also have the option of receiving a Certificate in Responsible Innovation by completing additional coursework. One of the PIs current students, Paul VanGilder, is currently a PhD Plus student. His dissertation will include a [redacted] (b)(4), (b)(6) Funds have been requested for a graduate student to attend *Science Outside the Lab*, presented by CSPO, which explores the relationships among science, policy, and societal outcomes in Washington, D.C. During the two-week workshop, students will meet and interact with the people who fund, regulate, shape, critique, publicize and study science, including congressional staffers, funding agency officers, lobbyists, regulators, journalists, academics, museum curators and others. These activities will advance discovery and understanding while promoting teaching, training, and learning.

Educ. Goal 4: Engage the public in scientific discourse

The PI will organize a public lecture and discussion on the social and ethical implications of neurorobotic systems and interactions through the "Science Café" series hosted by the Arizona Science Center. Attendees will be invited to tour the PI's research labs, as coordinated by the ASU Foundation Development Office. The PI will also work to develop an interactive exhibit for the Arizona Science Center on the interactions between humans and machines for elementary and middle school students and will deploy it locally for the benefit of school-aged children and the general public in the metropolitan Phoenix area. The proposed exhibit will enhance the permanent biology and brain W.O.N.D.E.R. Center exhibit seen by 400,000 visitors annually (intergenerational families, school children, teachers, and underserved youth). These activities will promote broad dissemination of the work to enhance scientific and technological understanding.

Results from Prior NSF Support

Christopher Buneo

IOS-0746398: *CAREER: Characterizing neural mechanisms of state estimation in the posterior parietal cortex, 05/15/2008-04/30/2014, $609,813.00*

Intellectual Merit: This project was aimed at improving our understanding of the role of the posterior parietal cortex (PPC) in the estimation of limb state (position and velocity). The primary goal of the proposed research was to characterize the mechanisms of integration of somatic (proprioceptive and efference copy) and visually-based limb position signals in the superior parietal lobule (SPL) and inferior parietal lobule (IPL). These goals were addressed using standard neurophysiological recording techniques combined with a virtual reality based behavioral control paradigm. To date this work has resulted in 7 journal articles (Apker et al., 2010; Apker et al., 2011; Buneo, 2011; Apker and Buneo, 2012; Shi and Buneo, 2012; Shi et al., 2013; Apker et al., 2015), 2 book chapters (Buneo, 2010; Buneo et al., 2011), 2 conference proceedings (Shi and Buneo, 2009; Shi and Buneo, 2011) and 11 abstracts with 2 more journal manuscripts currently under review or in preparation. The project has also enhanced the mentoring of 4 PhD students (1 female), 2 MS students (1 female), 6 undergraduates and 3 high school students (1 female).

Broader Impacts: We have engaged in outreach activities at one of the local school districts (Gilbert Unified), and have advised the projects of three students from the Project Lead the Way certified Biomedical Program at Campo Verde High in the local Gilbert Unified District (2 as summer interns).

Bijan Pesaran

BCS- 0955701: *CAREER: Neural circuit mechanisms of coordinated eye and hand movements, 6/15/2010-5/31/2015. $719,688.00*

Intellectual Merit: This project was aimed at improving our understanding of the role of interactions between regions of the posterior parietal cortex in the coordination of eye and arm movements. The primary goal of the proposed research was to identify the role of excitatory and inhibitory interactions between eye and arm related regions of the posterior parietal cortex. The goals were addressed using multiple-area multiple-electrode recordings in different regions of the brain and the development of novel techniques for signal analysis and experimental recordings. To date this work has resulted in 7 journal articles (Banerjee et al., 2010; Dean et al., 2011; Banerjee et al., 2012; Dean et al., 2012; Hagan et al., 2012; Markowitz et al., 2012; Markowitz et al., In press) and 1 book chapter (Wong and Pesaran, 2015), as well as 5 conference proceedings and 12 conference abstracts with two manuscripts currently under review and three manuscripts in preparation. The project has also enhanced the mentoring of three PhD students (one female), two masters students (one female), four undergraduates (2 female) and two research technicians (two female, under-represented minorities).

Broader Impacts: We have engaged in outreach activities to teach science classes in the New York Public School system engaging disadvantaged students at a local middle school in Brooklyn. We have developed a new class to teach undergraduate and graduate students methods of quantitative thinking. We have participated in outreach activities as part of the World Science Festival and the American Museum of Natural History in New York City.

Angelaki DE, Gu Y, DeAngelis GC (2009) Multisensory integration: psychophysics, neurophysiology, and computation. Curr Opin Neurobiol 19:452-458.
Apker GA, Buneo CA (2012) Contribution of execution noise to arm movement variability in three-dimensional space. J Neurophysiol 107:90-102.
Apker GA, Darling TK, Buneo CA (2010) Interacting noise sources shape patterns of arm movement variability in three-dimensional space. J Neurophysiol 104:2654-2666.
Apker GA, Karimi CP, Buneo CA (2011) Contributions of vision and proprioception to arm movement planning in the vertical plane. Neuroscience Letters 503:186-190.
Apker GA, Dyson K, Frantz G, Buneo CA (2015) Efficiency of visual feedback integration differs between dominant and non-dominant arms during a reaching task. Experimental Brain Research 233:317-327.
Avillac M, Ben Hamed S, Duhamel JR (2007) Multisensory integration in the ventral intraparietal area of the macaque monkey. J Neurosci 27:1922-1932.
Banerjee A, Dean HL, Pesaran B (2010) A Likelihood Method for Computing Selection Times in Spiking and Local Field Potential Activity. Journal of Neurophysiology 104:3705-3720.
Banerjee A, Dean HL, Pesaran B (2012) Parametric models to relate spike train and LFP dynamics with neural information processing. Frontiers in Computational Neuroscience 6.
Bauer M (2008) Multisensory integration: A functional role for inter-area synchronization? Curr Biol 18:R709-R710.
Bensmaia SJ, Miller LE (2014) Restoring sensorimotor function through intracortical interfaces: progress and looming challenges. Nature Reviews Neuroscience 15:313-325.
Blanke O (2012) Multisensory brain mechanisms of bodily self-consciousness. Nature Reviews Neuroscience 13:556-571.
Bohil CJ, Alicea B, Biocca FA (2011) Virtual reality in neuroscience research and therapy. Nature Reviews Neuroscience 12:752-762.
Bokil H, Andrews P, Kulkarni JE, Mehta S, Mitra PP (2010) Chronux: A platform for analyzing neural signals. Journal of Neuroscience Methods 192:146-151.
Bremmer F, Klam F, Duhamel JR, Ben Hamed S, Graf W (2002) Visual-vestibular interactive responses in the macaque ventral intraparietal area (VIP). Eur J Neurosci 16:1569-1586.
Brovelli A, Ding MZ, Ledberg A, Chen YH, Nakamura R, Bressler SL (2004) Beta oscillations in a large-scale sensorimotor cortical network: Directional influences revealed by Granger causality. Proceedings of the National Academy of Sciences of the United States of America 101:9849-9854.
Buneo CA (2010) Neural Representations of Intended Movement. In: Encyclopedia of Behavioral Neuroscience (Koob G, Le Moal M, Thompson R, eds), pp 356-361. Oxford: Elsevier.
Buneo CA (2011) Analyzing neural responses with vector fields. J Neurosci Methods 197:109-117.
Buneo CA, Andersen RA (2012) Integration of target and hand position signals in the posterior parietal cortex: effects of workspace and hand vision. J Neurophysiol 108:187-199.
Buneo CA, Apker GA, Shi Y (2011) Probing neural correlates of cue integration. In: Sensory Cue Integration (Trommershauser J, Kording K, Landy MS, eds), pp 317-332. New York: Oxford.
Buzsaki G (2010) Neural Syntax: Cell Assemblies, Synapsembles, and Readers. Neuron 68:362-385.
Canolty RT, Edwards E, Dalal SS, Soltani M, Nagarajan SS, Kirsch HE, Berger MS, Barbaro NM, Knight RT (2006) High gamma power is phase-locked to theta oscillations in human neocortex. Science 313:1626-1628.
Cavada C, Goldman-Rakic PS (1989a) Posterior parietal cortex in rhesus monkey: I. Parcellation of areas based on distinctive limbic and sensory corticocortical connections. J Comp Neurol 287:393-421.
Cavada C, Goldman-Rakic PS (1989b) Posterior parietal cortex in rhesus monkey: II. Evidence for segregated corticocortical networks linking sensory and limbic areas with the frontal lobe. J Comp Neurol 287:422-445.
Chandrasekaran C, Ghazanfar AA (2009) Different Neural Frequency Bands Integrate Faces and Voices Differently in the Superior Temporal Sulcus. J Neurophysiol 101:773-788.
Dadarlat MC, O'Doherty JE, Sabes PN (2015) A learning-based approach to artificial sensory feedback leads to optimal integration. Nature Neuroscience 18:138-+.
de Vignemont F (2010) Body schema and body image-Pros and cons. Neuropsychologia 48:669-680.
Dean HL, Hagan MA, Pesaran B (2012) Only Coherent Spiking in Posterior Parietal Cortex Coordinates Looking and Reaching. Neuron 73:829-841.

Dean HL, Marti D, Tsui E, Rinzel J, Pesaran B (2011) Reaction Time Correlations during Eye-Hand Coordination: Behavior and Modeling. Journal of Neuroscience 31:2399-2412.
Engel AK, Fries P (2010) Beta-band oscillations - signalling the status quo? Current Opinion in Neurobiology 20:156-165.
Ernst MO, Banks MS (2002) Humans integrate visual and haptic information in a statistically optimal fashion. Nature 415:429-433.
Georgopoulos AP, Caminiti R, Kalaska JF (1984) Static spatial effects in motor cortex and area 5: quantitative relations in a two-dimensional space. Exp Brain Res 54:446-454.
Ghazanfar AA, Maier JX, Hoffman KL, Logothetis NK (2005) Multisensory integration of dynamic faces and voices in rhesus monkey auditory cortex. J Neurosci 25:5004-5012.
Graziano MS, Yap GS, Gross CG (1994) Coding of visual space by premotor neurons. Science 266:1054-1057.
Graziano MS, Cooke DF, Taylor CS (2000) Coding the location of the arm by sight. Science 290:1782-1786.
Graziano MSA (1999) Where is my arm? The relative role of vision and proprioception in the neuronal representation of limb position. P Natl Acad Sci USA 96:10418-10421.
Graziano MSA, Gross CG, Taylor CSR, Moore T (2004) A system of multimodal areas in the primate brain. In: Crossmodal Space and Crossmodal Attention. (Spence C, Driver J, eds), pp 51-67. New York: Oxford University Press U.S.A.
Gu Y, Angelaki DE, DeAngelis GC (2008) Neural correlates of multisensory cue integration in macaque MSTd. Nat Neurosci 11:1201-1210.
Hagan MA, Dean HL, Pesaran B (2012) Spike-field activity in parietal area LIP during coordinated reach and saccade movements. Journal of Neurophysiology 107:1275-1290.
Harris KD, Mrsic-Flogel TD (2013) Cortical connectivity and sensory coding. Nature 503:51-58.
Jarvis MR, Mitra PP (2001) Sampling properties of the spectrum and coherency of sequences of action potentials. Neural Comput 13:717-749.
Kadunce DC, Vaughan JW, Wallace MT, Benedek G, Stein BE (1997) Mechanisms of within- and cross-modality suppression in the superior colliculus. J Neurophysiol 78:2834-2847.
Kammers MPM, de Vignemont F, Verhagen L, Dijkerman HC (2009a) The rubber hand illusion in action. Neuropsychologia 47:204-211.
Kammers MPM, Verhagen L, Dijkerman HC, Hogendoorn H, De Vignemont F, Schutter DJLG (2009b) Is This Hand for Real? Attenuation of the Rubber Hand Illusion by Transcranial Magnetic Stimulation over the Inferior Parietal Lobule. Journal of Cognitive Neuroscience 21:1311-1320.
Kanayama N, Sato A, Ohira H (2007) Crossmodal effect with rubber hand illusion and gamma-band activity. Psychophysiology 44:392-402.
Kayser C, Logothetis NK, Panzeri S (2010) Visual Enhancement of the Information Representation in Auditory Cortex. Current Biology 20:19-24.
Kording KP, Wolpert DM (2004) Bayesian integration in sensorimotor learning. Nature 427:244-247.
Lacquaniti F, Guigon E, Bianchi L, Ferraina S, Caminiti R (1995) Representing spatial information for limb movement: role of area 5 in the monkey. Cereb Cortex 5:391-409.
Lakatos P, Chen CM, O'Connell MN, Mills A, Schroeder CE (2007) Neuronal oscillations and multisensory interaction in primary auditory cortex. Neuron 53:279-292.
Maier JX, Chandrasekaran C, Ghazanfar AA (2008) Integration of bimodal looming signals through neuronal coherence in the temporal lobe. Curr Biol 18:963-968.
Markowitz DA, C. C, Pesaran B (In press) Multiple Component Networks Support Working Memory in Prefrontal Cortex. Proc Natl Acad Sci U S A.
Markowitz DA, Wong YT, Gray CM, Pesaran B (2012) Optimizing the Decoding of Movement Goals from Local Field Potentials in Macaque Cortex. Journal of Neuroscience 32:4702-4702.
Matelli M, Camarda R, Glickstein M, Rizzolatti G (1986) Afferent and efferent projections of the inferior area-6 in the macaque monkey. Journal of Comparative Neurology 251:281-298.
Meredith MA, Stein BE (1983) Interactions among converging sensory inputs in the superior colliculus. Science 221:389-391.
Meredith MA, Stein BE (1986a) Spatial factors determine the activity of multisensory neurons in cat superior colliculus. Brain Res 365:350-354.
Meredith MA, Stein BE (1986b) Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. J Neurophysiol 56:640-662.

Meredith MA, Stein BE (1996) Spatial determinants of multisensory integration in cat superior colliculus neurons. J Neurophysiol 75:1843-1857.
Meredith MA, Nemitz JW, Stein BE (1987) Determinants of Multisensory Integration in Superior Colliculus Neurons .1. Temporal Factors. J Neurosci 7:3215-3229.
Mitra PP, Pesaran B (1999) Analysis of dynamic brain imaging data. Biophys J 76:691-708.
Morgan ML, DeAngelis GC, Angelaki DE (2008) Multisensory integration in macaque visual cortex depends on cue reliability. Neuron 59:662-673.
Mountcastle VB, Lynch JC, Georgopoulos A, Sakata H, Acuna C (1975) Posterior parietal association cortex of the monkey: command functions for operations within extrapersonal space. J Neurophysiol 38:871-908.
Muakkassa KF, Strick PL (1979) Frontal lobe inputs to primate motor cortex - evidence for 4 somatotopically organized premotor areas. Brain Research 177:176-182.
Mulliken GH, Musallam S, Andersen RA (2008) Forward estimation of movement state in posterior parietal cortex. PNAS USA 105:8170-8177.
Nawrot MP, Boucsein C, Molina VR, Riehle A, Aertsen A, Rotter S (2008) Measurement of variability dynamics in cortical spike trains. J Neurosci Methods 169:374-390.
Neal JW, Pearson RC, Powell TP (1987) The cortico-cortical connections of area 7b, PF, in the parietal lobe of the monkey. Brain Res 419:341-346.
Newport R, Pearce R, Preston C (2010) Fake hands in action: embodiment and control of supernumerary limbs. Experimental Brain Research 204:385-395.
Perrodin C, Kayser C, Logothetis NK, Petkov CI (2015) Natural asynchronies in audiovisual communication signals regulate neuronal multisensory interactions in voice-sensitive cortex. Proceedings of the National Academy of Sciences of the United States of America 112:273-278.
Pouget A, Dayan P, Zemel R (2000) Information processing with population codes. Nat Rev Neurosci 1:125-132.
(b) (4) [redacted].
Rognini G, Senguel A, Aspell JE, Salomon R, Bleuler H, Blanke O (2013) Visuo-tactile integration and body ownership during self-generated action. European Journal of Neuroscience 37:1120-1129.
Rozzi S, Calzavara R, Belmalih A, Borra E, Gregoriou GG, Matelli M, Luppino G (2006) Cortical connections of the inferior parietal cortical convexity of the macaque monkey. Cerebral Cortex 16:1389-1417.
Scherberger H, Jarvis MR, Andersen RA (2005) Cortical local field potential encodes movement intentions in the posterior parietal cortex. Neuron 46:347-354.
Schoffelen JM, Oostenveld R, Fries P (2005) Neuronal coherence as a mechanism of effective corticospinal interaction. Science 308:111-113.
Schwartz AB, Moran DW, Reina GA (2004) Differential representation of perception and action in the frontal cortex. Science 303:380-383.
Senkowski D, Schneider TR, Foxe JJ, Engel AK (2008) Crossmodal binding through neural coherence: implications for multisensory processing. Trends in Neurosciences 31:401-409.
Shi Y, Buneo CA (2009) Exploring the role of sensor noise in movement variability. In: IEEE Engineering in Medicine and Biology Society, pp 4970-4973. Minneapolis, MN.
Shi Y, Buneo CA (2011) Neural mechanisms of limb position estimation in the primate brain. In: Conf. Proc. IEEE Eng. Med. Biol. Soc. Boston, MA.
Shi Y, Buneo CA (2012) Movement variability resulting from different noise sources: A simulation study. Human Movement Science 31:772-790.
Shi Y, Apker G, Buneo CA (2013) Multimodal representation of limb endpoint position in the posterior parietal cortex. J Neurophysiol 109:2097-2107.
Shokur S, O'Doherty JE, Winans JA, Bleuler H, Lebedev MA, Nicolelis MAL (2013) Expanding the primate body schema in sensorimotor cortex by virtual touches of an avatar. Proceedings of the National Academy of Sciences of the United States of America 110:15121-15126.
Siegel M, Donner TH, Engel AK (2012) Spectral fingerprints of large-scale neuronal interactions. Nature Reviews Neuroscience 13:121-134.
Sober SJ, Sabes PN (2003) Multisensory integration during motor planning. J Neurosci 23:6982-6992.
Spence C, Pavani F, Driver J (2004) Spatial constraints on visual-tactile cross-modal distractor congruency effects. Cognitive Affective & Behavioral Neuroscience 4:148-169.

Sugihara T, Diltz MD, Averbeck BB, Romanski LM (2006) Integration of auditory and visual communication information in the primate ventrolateral prefrontal cortex. J Neurosci 26:11138-11147.
Taig E, Kueper M, Theysohn N, Timmann D, Donchin O (2012) Deficient Use of Visual Information in Estimating Hand Position in Cerebellar Patients. Journal of Neuroscience 32:16274-16284.
Tanne-Gariepy J, Rouiller EM, Boussaoud D (2002) Parietal inputs to dorsal versus ventral premotor areas in the macaque monkey: evidence for largely segregated visuomotor pathways. Experimental Brain Research 145:91-103.
Tieri G, Tidoni E, Pavone EF, Aglioti SM (2015) Mere observation of body discontinuity affects perceived ownership and vicarious agency over a virtual hand. Experimental Brain Research 233:1247-1259.
Tort ABL, Komorowski R, Eichenbaum H, Kopell N (2010) Measuring Phase-Amplitude Coupling Between Neuronal Oscillations of Different Frequencies. (vol 104, pg 1195, 2010). Journal of Neurophysiology 104:2302-2302.
Toth LA, Gardiner TW (2000) Food and water restriction protocols: Physiological and behavioral considerations. Contemporary Topics in Laboratory Animal Science 39:9-17.
Tsakiris M, Haggard P (2005) The rubber hand illusion revisited: Visuotactile integration and self-attribution. Journal of Experimental Psychology-Human Perception and Performance 31:80-91.
Tsakiris M, Prabhu G, Haggard P (2006) Having a body versus moving your body: How agency structures body-ownership. Consciousness and Cognition 15:423-432.
van Atteveldt N, Murray MM, Thut G, Schroeder CE (2014) Multisensory Integration: Flexible Use of General Operations. Neuron 81:1240-1253.
van Beers RJ, Wolpert DM, Haggard P (2002) When feeling is more important than seeing in sensorimotor adaptation. Curr Biol 12:834-837.
van Kerkoerle T, Self MW, Dagnino B, Gariel-Mathis M-A, Poort J, van der Togt C, Roelfsema PR (2014) Alpha and gamma oscillations characterize feedback and feedforward processing in monkey visual cortex. Proceedings of the National Academy of Sciences of the United States of America 111:14332-14341.
Womelsdorf T, Schoffelen J-M, Oostenveld R, Singer W, Desimone R, Engel AK, Fries P (2007) Modulation of neuronal interactions through neuronal synchronization. Science 316:1609-1612.
Wong YT, Pesaran B (2015) Decoding Field Potentials. In: Encyclopedia of Computational Neuroscience (D J, R J, eds), pp 965-968. New York: Springer.
Zanos TP, Mineault PJ, Pack CC (2011) Removal of Spurious Correlations Between Spikes and Local Field Potentials. Journal of Neurophysiology 105:474-486.
Zhou YD, Fuster JM (2000) Visuo-tactile cross-modal associations in cortical somatosensory cells. Proc Natl Acad Sci U S A 97:9777-9782.

Christopher A. Buneo, Ph.D.

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Biographical Sketch of Bijan Pesaran

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SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION **Arizona State University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted	
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**	AWARD NO.			

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**1**) POST DOCTORAL SCHOLARS					
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**1**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					

D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)			
Data server	$ **10,000**		
Plexon Data Acquisition System	**115,000**		
Virtual Reality Training Platform	**107,000**		
TOTAL EQUIPMENT		**232,000**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)		**16,690**	
2. FOREIGN		**0**	
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS	$ **0**		
2. TRAVEL	**0**		
3. SUBSISTENCE	**0**		
4. OTHER	**0**		
TOTAL NUMBER OF PARTICIPANTS (**0**)	TOTAL PARTICIPANT COSTS	**0**	
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		**71,952**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		**0**	
3. CONSULTANT SERVICES		**0**	
4. COMPUTER SERVICES		**0**	
5. SUBAWARDS		**0**	
6. OTHER		**16,831**	
TOTAL OTHER DIRECT COSTS		**88,783**	
H. TOTAL DIRECT COSTS (A THROUGH G)		(b) (4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base** (b) (4) [redacted]			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)		**580,281**	
K. SMALL BUSINESS FEE		**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)		**580,281**	
M. COST SHARING PROPOSED LEVEL $ **Not Shown**	AGREED LEVEL IF DIFFERENT $		

PI/PD NAME **Christopher Buneo**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey Bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1558131

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION **Arizona State University**			FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**1**) POST DOCTORAL SCHOLARS					
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**1**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**16,690**	
2. FOREIGN				**3,600**	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ **0**					
2. TRAVEL **0**					
3. SUBSISTENCE **0**					
4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**68,952**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**2,500**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**18,177**	
TOTAL OTHER DIRECT COSTS				**89,629**	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b) (4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base:** (b) (4) [redacted]					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**361,474**	
K. SMALL BUSINESS FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**361,474**	
M. COST SHARING PROPOSED LEVEL $ **Not Shown**	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME **Christopher Buneo**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey Bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

2 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION **Arizona State University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months	Funds Requested By	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b)(4), (b)(6) [redacted]		
2.			
3.			
4.			
5.			
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAG			
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)			
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (**1**) POST DOCTORAL SCHOLARS			
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)			
3. (**1**) GRADUATE STUDENTS			
4. (**0**) UNDERGRADUATE STUDENTS			
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)			
6. (**0**) OTHER			
TOTAL SALARIES AND WAGES (A + B)			
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)			
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)			
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE			
TOTAL EQUIPMENT		**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)		**16,690**	
2. FOREIGN		**0**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**			
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS		**0**	
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		**33,952**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		**2,500**	
3. CONSULTANT SERVICES		**0**	
4. COMPUTER SERVICES		**0**	
5. SUBAWARDS		**0**	
6. OTHER		**19,631**	
TOTAL OTHER DIRECT COSTS		**56,083**	
H. TOTAL DIRECT COSTS (A THROUGH G)		(b) (4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base:** (b) (4) [redacted] TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)		**310,638**	
K. SMALL BUSINESS FEE		**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)		**310,638**	
M. COST SHARING PROPOSED LEVEL $ **Not Shown** AGREED LEVEL IF DIFFERENT $			

PI/PD NAME **Christopher Buneo**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey Bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

3 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1558151

SUMMARY PROPOSAL BUDGET YEAR 4

ORGANIZATION **Arizona State University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**1**) POST DOCTORAL SCHOLARS					
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**1**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**16,690**	
2. FOREIGN				**3,600**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**57,952**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**3,750**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**21,202**	
TOTAL OTHER DIRECT COSTS				**82,904**	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b) (4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base** (b) (4) [redacted] TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**364,427**	
K. SMALL BUSINESS FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**364,427**	
M. COST SHARING PROPOSED LEVEL $ **Not Shown**	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME **Christopher Buneo**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey Bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

4 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 5

ORGANIZATION: **Arizona State University**	FOR NSF USE ONLY: PROPOSAL NO.	DURATION (months): Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Christopher Buneo**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months	Funds Requested By	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b)(4), (b)(6) [redacted]		
2.			
3.			
4.			
5.			
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAG			
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)			
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (**1**) POST DOCTORAL SCHOLARS			
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)			
3. (**1**) GRADUATE STUDENTS			
4. (**0**) UNDERGRADUATE STUDENTS			
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)			
6. (**0**) OTHER			
TOTAL SALARIES AND WAGES (A + B)			
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)			
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)			
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE			
TOTAL EQUIPMENT		**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)		**16,690**	
2. FOREIGN		**0**	
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS $ **0**			
2. TRAVEL **0**			
3. SUBSISTENCE **0**			
4. OTHER **0**			
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS		**0**	
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		**33,952**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		**3,750**	
3. CONSULTANT SERVICES		**0**	
4. COMPUTER SERVICES		**0**	
5. SUBAWARDS		**0**	
6. OTHER		**22,899**	
TOTAL OTHER DIRECT COSTS		(b) (4) [redacted]	
H. TOTAL DIRECT COSTS (A THROUGH G)			
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base** (b) (4) [redacted]			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)		**331,434**	
K. SMALL BUSINESS FEE		**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)		**331,434**	
M. COST SHARING PROPOSED LEVEL $ **Not Shown**	AGREED LEVEL IF DIFFERENT $		

PI/PD NAME: **Christopher Buneo**	FOR NSF USE ONLY		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*: **Lindsey Bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1558131

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION **Arizona State University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**5**) POST DOCTORAL SCHOLARS					
2. (**5**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**5**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEED		$	**232,000**		
TOTAL EQUIPMENT				**232,000**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**83,450**	
2. FOREIGN				**7,200**	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ **0**					
2. TRAVEL **0**					
3. SUBSISTENCE **0**					
4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**266,760**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**12,500**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**98,740**	
TOTAL OTHER DIRECT COSTS				**378,000**	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b) (4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**1,948,254**	
K. SMALL BUSINESS FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**1,948,254**	
M. COST SHARING PROPOSED LEVEL $ **Not Shown**	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME **Christopher Buneo**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey Bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1558131

Budget Justification

A. Senior Personnel

Christopher Buneo, Principal Investigator (b)(4), (b)(6) [redacted] Dr. Buneo will be responsible for leadership and administration of the research project as well the experimental design, data analyses and preparation of the manuscripts. He will also supervise and train one PhD student and co-mentor a postdoctoral fellow with the Co-Investigator.

B. Other Personnel

We request (b) (4) [redacted], each year of the project for one postdoctoral fellow and one graduate student to work with the investigators for all five years of the project. We also request (b) (4) [redacted] for a laboratory coordinator.

Postdoctoral fellow (b) (4) [redacted]**):** The postdoc will be trained to design experimental protocols, acquire data, perform data analyses, prepare oral and written reports for lab meetings and conference presentation, and prepare manuscripts. The postdoc will also help directly supervise the PhD student.

PhD student (b) (4) [redacted]**):** One PhD student is allocated at an effort level of (b) (4) [redacted] per week. The student will be trained to design experimental protocols and perform pilot testing, learn data acquisition and analyses, prepare oral and written reports for lab meetings and conference presentation, and help prepare manuscripts.

(b)(4), (b)(6) [redacted] **Laboratory coordinator** (b) (4), (b) (6) [redacted]): The coordinator will be responsible for managing the non-human primates and providing infrastructure support for the primate lab.

C. Fringe Benefits (Employee Related Expenses)

Arizona State University defines fringe benefits as direct costs and estimates fringe benefits at a standard percent of salary that is uniformly applied across the organization. The estimated cost of ERE associated with the personnel costs for this proposal and is based upon the following rates for FY 2016 and thereafter:

ERE Rate Estimates	FACULTY	STAFF	POST-DOC'S	STUDENTS	RA/TA
FY 2016 Estimated Rate	(b) (4) [redacted]				
FY 2017 Estimated Rate					
FY 2018 Estimated Rate					
FY 2019 Estimated Rate					
FY 2020 Estimated Rate					

** A rate o* (b) (4) [redacted] *scalation applies for out years beyond 2020*

D. Equipment (Year One $232,000):

Plexon Data Acquisition System	$115,000
Virtual Reality Training Platform (Motion Analysis Tracking System $80,000, Custom 3ds Max Live Characters Plugin $20,000, SIMM (Software for musculoskeletal modeling $7,000)	$107,000
Data server	$10,000
Total	**$232,000**

Funds are requested for a Plexon data acquisition system that will enable recording from three cortical areas simultaneously, a key component of the proposed work. Funds are also requested for the construction of the virtual reality training platform developed by the (b)(4), (b)(6) [redacted] which will enable the visual feedback manipulations that are a cornerstone of the project ($107,000 total). This includes a motion tracking system from Motion Analysis, a custom

3ds Max live characters plugin, and SIMM (Software for Musculoskeletal Modeling). Lastly, funds are requested to build a data server for the research team at ASU ($10,000).

E. Travel

Domestic Travel	Year 1	Year 2	Year 3	Year 4	Year 5
Conference (TBD)	3 Travelers	3 Travelers	3 Travelers	3 Travelers	3 Travelers
Airfare @$500 ea	$1,500	$1,500	$1,500	$1,500	$1,500
Lodging 3 nights@$150	$1,350	$1,350	$1,350	$1,350	$1,350
Per diem 3 days@$70	$630	$630	$630	$630	$630
Ground Trans@$70	$210	$210	$210	$210	$210
Misc. 3 days@$25	$225	$225	$225	$225	$225
Conferences Total	$3,915	$3,915	$3,915	$3,915	$3,915
New York (Postdoc/Stud)	1 Traveler	1 Traveler	1 Traveler	1 Traveler	1 Traveler
Airfare@$500 ea	$500	$500	$500	$500	$500
Lodging 14 nights@$304	$4,256	$4,256	$4,256	$4,256	$4,256
Per diem 14 days@$71	$994	$994	$994	$994	$994
Ground Trans@$100	$100	$100	$100	$100	$100
Misc. 14 days@$25	$350	$350	$350	$350	$350
Postdoc/Student Total	$6,200	$6,200	$6,200	$6,200	$6,200
New York (PI)	1 Traveler	1 Traveler	1 Traveler	1 Traveler	1 Traveler
Airfare@$500	$500	$500	$500	$500	$500
Lodging 3 nights@$304	$912	$912	$912	$912	$912
Per diem 3 days@$71	$213	$213	$213	$213	$213
Ground Trans@$100	$100	$100	$100	$100	$100
Misc. 3 days@$25	$75	$75	$75	$75	$75
PI New York Trip	$1,800	$1,800	$1,800	$1,800	$1,800
Washington, DC (Student)	1 Traveler	1 Traveler	1 Traveler	1 Traveler	1 Traveler
Airfare@$450	$450	$450	$450	$450	$450
All inclusive $4,000	$4,000	$4,000	$4,000	$4,000	$4,000
Misc/13 days@$25 per day	$325	$325	$325	$325	$325
Total Washington DC	$4,775	$4,775	$4,775	$4,775	$4,775
Total domestic travel	$16,690	$16,690	$16,690	$16,690	$16,690
Foreign Travel (TBD)		1 Traveler		1 Traveler	
Airfare@$1,500		$1,500		$1,500	
Lodging 5 nights@$200		$1,000		$1,000	
Per diem 6 days@$100		$600		$600	
Ground Trans@$200		$200		$200	
Misc. 6 days@$50		$300		$300	
Total Foreign Travel		$3,600		$3,600	

We have requested support for the PI (1 domestic meeting/year; 1 international meeting in years 2 and 4) and two trainees (Postdoc and PhD student; 1 domestic meeting/year) to attend high-impact scientific meetings such the Annual Meetings of the Society for Neuroscience and Society for Neural Control of Movement or the Computational and Systems Neuroscience (Cosyne) to present findings generated by this project. We have also requested support for the PI (1 trip/year) and either the postdoctoral fellow or PhD student (1 trip/year) to visit the Co-Investigator's institution to discuss research findings. In the case of the postdoc/student, this trip will be an immersive 2-week experience which will also involve hands-on instruction from the Co-Investigator (Pesaran) on advanced data analysis techniques relevant to the project. Lastly, as an additional training opportunity, funds have been requested for a graduate student to attend *Science Outside the Lab*, hosted by ASU's Consortium for Science, Policy & Outcomes (CSPO), an immersive training experience which explores the relationships among science, policy, and societal outcomes in Washington, D.C.

Note: The travel budget was estimated in accordance with the University's travel policy (see http://www.asu.edu/aad/manuals/fin/index.html#500) based on current air fares, current ASU authorized per diem rates (http://www.gao.az.gov/publications/SAAM/Supp_I_trvrates-012308.pdf), airport shuttle services, and, if applicable, conference registration fees and/or car rental.

G. Other Direct Costs

Surgical and General Materials and Supplies: Funds are requested for surgery related expenses and other materials and supplies necessary for the successful completion of the proposed work.

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Rhesus macaque monkeys 4@$8,250 ea	$33,000	$0	$0	$0	$0
Animal maintenance	$23,952	$23,952	$18,952	$18,952	$18,952
Computers 2@$3,000	$0	$6,000	$0	$0	$0
Microelectrode arrays@$4,000 ea	$0	$24,000	$0	$24,000	$0
Materials	$10,000	$10,000	$10,000	$10,000	$10,000
Equipment maintenance	$5,000	$5,000	$5,000	$5,000	$5,000
Total	**$71,952**	**$68,952**	**$33,952**	**57,952**	**$33,952**

These expenses include animal purchases (4 Rhesus macaque monkeys in year 1; $33,000 total including transportation costs), computers (2 in year 1; $6000 total), animal per diems (years 1-5; $104,760 total), microelectrode arrays (6 in years 2 and 4; $48,000 total), supplies for implantation and maintenance of the arrays, fixation pedestals, and associated hardware ($10,000 years 1-5; $50,000 total), and materials and supplies for maintenance of primate chairs and testing apparatus ($5,000 in years 1-5; $25,000 total).

Publication costs: Funds are requested ($12,500 total) to support publications in high impact factor journals such as *Nature Neuroscience, Neuron, Journal of Neuroscience and Journal of Neurophysiology*.

Tuition Remission: Tuition for graduate students is included as a mandatory benefit for graduate students employed as the university and is charged to projects in proportion to the amount of the effort the graduate student will work on the project. ***Tuition charges are exempt from the Facilities and Administrative (F&A) costs.***

H. Facilities and Administration (F&A) Costs

Indirect costs are calculated on Modified Total Direct Costs (MTDC) using F&A rates approved by US Department of Health and Human Services. F&A rates for Organized Research FY 16 and beyond is assessed at 54.5%, and are specified in the June 15, 2015 rate agreement. MTDC is comprised of salaries and wages, fringe benefits, materials and supplies, services, travel, and subgrant/subcontract up to $25,000. Exclusions from MTDC include equipment, tuition remission, and subgrants/subcontracts exceeding $25,000.

SUMMARY PROPOSAL BUDGET

YEAR 1

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
New York University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Bijan Pesaran

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Bijan Pesaran - Associate Professor**	[redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					

D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEED			
Computer Server	**$ 10,000**		
TOTAL EQUIPMENT		**10,000**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)		**5,000**	
2. FOREIGN		**0**	
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS $	**0**		
2. TRAVEL	**0**		
3. SUBSISTENCE	**0**		
4. OTHER	**0**		
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS		**0**	
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		**0**	
3. CONSULTANT SERVICES		**0**	
4. COMPUTER SERVICES		**0**	
5. SUBAWARDS		**0**	
6. OTHER		**0**	
TOTAL OTHER DIRECT COSTS		**0**	
H. TOTAL DIRECT COSTS (A THROUGH G)		[redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct Costs (Rate: 58.5000, Base** [redacted]			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)		**59,338**	
K. SMALL BUSINESS FEE		**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)		**59,338**	

M. COST SHARING PROPOSED LEVEL $ **Not Shown** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Bijan Pesaran

ORG. REP. NAME*
Nancy Daneau

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1557886

SUMMARY PROPOSAL BUDGET

YEAR 2

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
New York University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Bijan Pesaran

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Bijan Pesaran - Associate Professor	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)					
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS					
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (0) GRADUATE STUDENTS					
4. (0) UNDERGRADUATE STUDENTS					
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (0) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				5,125	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				0	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Modified Total Direct Costs (Rate: 58.5000, Base (b)(4), (b)(6) [redacted]					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				50,573	
K. SMALL BUSINESS FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				50,573	

M. COST SHARING PROPOSED LEVEL $ Not Shown AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Bijan Pesaran

ORG. REP. NAME*
Nancy Daneau

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

2 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1557886

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION New York University	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR Bijan Pesaran	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Bijan Pesaran - Associate Professor	[redacted]				
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS					
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (0) GRADUATE STUDENTS					
4. (0) UNDERGRADUATE STUDENTS					
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (0) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					

	Funds Requested By proposer	Funds granted by NSF (if different)
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)		
TOTAL EQUIPMENT	0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)	5,253	
2. FOREIGN	0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0		
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS	0	
G. OTHER DIRECT COSTS		
1. MATERIALS AND SUPPLIES	0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION	0	
3. CONSULTANT SERVICES	0	
4. COMPUTER SERVICES	0	
5. SUBAWARDS	0	
6. OTHER	0	
TOTAL OTHER DIRECT COSTS	0	
H. TOTAL DIRECT COSTS (A THROUGH G)	[redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Modified Total Direct Costs (Rate: 58.5000, Base [redacted]		
TOTAL INDIRECT COSTS (F&A)		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)	51,836	
K. SMALL BUSINESS FEE	0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	51,836	

M. COST SHARING PROPOSED LEVEL $ Not Shown | AGREED LEVEL IF DIFFERENT $

PI/PD NAME Bijan Pesaran	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* Nancy Daneau	Date Checked	Date Of Rate Sheet	Initials - ORG

3 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 4

ORGANIZATION: **New York University**	FOR NSF USE ONLY				
	PROPOSAL NO.	DURATION (months) Proposed	Granted		
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Bijan Pesaran**	AWARD NO.				
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Bijan Pesaran - Associate Professor**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAG					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**5,384**	
2. FOREIGN				**0**	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ **0**					
2. TRAVEL **0**					
3. SUBSISTENCE **0**					
4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**0**	
TOTAL OTHER DIRECT COSTS				**0**	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct Costs (Rate: 58.5000, Base** (b)(4), (b)(6) [redacted]					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**52,401**	
K. SMALL BUSINESS FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**52,401**	
M. COST SHARING PROPOSED LEVEL $ **Not Shown**	AGREED LEVEL IF DIFFERENT $				
PI/PD NAME: **Bijan Pesaran**	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION				
ORG. REP. NAME*: **Nancy Daneau**	Date Checked	Date Of Rate Sheet	Initials - ORG		

4 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1557886

SUMMARY PROPOSAL BUDGET

YEAR 5

FOR NSF USE ONLY			
ORGANIZATION: New York University	PROPOSAL NO.	DURATION (months)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: Bijan Pesaran	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Bijan Pesaran - Associate Professor	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS					
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (0) GRADUATE STUDENTS					
4. (0) UNDERGRADUATE STUDENTS					
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (0) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					

	Funds Requested By proposer	Funds granted by NSF (if different)
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)		
TOTAL EQUIPMENT	0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)	5,519	
2. FOREIGN	0	
F. PARTICIPANT SUPPORT COSTS		
1. STIPENDS $ 0		
2. TRAVEL 0		
3. SUBSISTENCE 0		
4. OTHER 0		
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS	0	
G. OTHER DIRECT COSTS		
1. MATERIALS AND SUPPLIES	0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION	0	
3. CONSULTANT SERVICES	0	
4. COMPUTER SERVICES	0	
5. SUBAWARDS	0	
6. OTHER	0	
TOTAL OTHER DIRECT COSTS	0	
H. TOTAL DIRECT COSTS (A THROUGH G)	(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Modified Total Direct Costs (Rate: 58.5000, Base: (b)(4), (b)(6) [redacted]		
TOTAL INDIRECT COSTS (F&A)		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)	53,711	
K. SMALL BUSINESS FEE	0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	53,711	

M. COST SHARING PROPOSED LEVEL $ Not Shown | AGREED LEVEL IF DIFFERENT $

PI/PD NAME: Bijan Pesaran	**FOR NSF USE ONLY**		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*: Nancy Daneau	Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1557886

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION	FOR NSF USE ONLY		
New York University	PROPOSAL NO.	DURATION (months)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR	AWARD NO.		
Bijan Pesaran			

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months	Funds Requested By proposer	Funds granted by NSF (if different)
1. Bijan Pesaran - Associate Professor	(b)(4), (b)(6) [redacted]		
2.			
3.			
4.			
5.			
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAG			
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)			
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (0) POST DOCTORAL SCHOLARS			
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)			
3. (0) GRADUATE STUDENTS			
4. (0) UNDERGRADUATE STUDENTS			
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)			
6. (0) OTHER			
TOTAL SALARIES AND WAGES (A + B)			
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)			
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)			
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)	$ 10,000		
TOTAL EQUIPMENT		10,000	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)		26,281	
2. FOREIGN		0	
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS $ 0			
2. TRAVEL 0			
3. SUBSISTENCE 0			
4. OTHER 0			
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS		0	
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		0	
3. CONSULTANT SERVICES		0	
4. COMPUTER SERVICES		0	
5. SUBAWARDS		0	
6. OTHER		0	
TOTAL OTHER DIRECT COSTS			
H. TOTAL DIRECT COSTS (A THROUGH G)		(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)		267,859	
K. SMALL BUSINESS FEE		0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)		267,859	
M. COST SHARING PROPOSED LEVEL $ Not Shown	AGREED LEVEL IF DIFFERENT $		

PI/PD NAME	FOR NSF USE ONLY		
Bijan Pesaran	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG
Nancy Daneau			

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

1557886

Budget Justification

A. Salaries and Wages:--Senior Personnel

Bijan Pesaran, Co-Investigator [redacted])

Functions: Responsible for the oversight of the Pesaran lab component of the project. He will coordinate with the coPI Buneo and postdoctoral fellow to design experiments, analyze the data and publish the work. Finally, he will be responsible for interfacing with the Arizona State University, the lead organization, on all budgetary and other administrative issues. The total salary requested for this project is $[redacted]

B. Salaries and Wages— Other Personnel

N/A

C. Fringe Benefits:

Regular employee incur fringe benefit costs at a rate of 28.5% of salary costs, for the period beginning 09/01/2014 to 08/30/2017, and provisional thereafter, per the University's negotiated rate agreement with the DHHS, signed 8/19/2014. The total fringe for this project is [redacted]

D. Permanent Equipment

Computer Server: A data storage server and computer will be purchased in year 1 to support the data storage and computation for the project, the total requested for the server is $10,000.

E. Travel

1. Domestic Travel for attending a professional meeting

Funds are requested for the co-I to visit the lead organization, Arizon State University each year and to attend a conference at which results will be presented. Yr1: $5,000, Yr2: $5,125, Yr3: $5,253, Yr4: $5,384, Yr5: $5,519

2. Foreign Travel: N/A

F. Participant Support Costs

1. Stipends: N/A

2. Travel: N/A

G. Other Direct Costs

1. Materials and Supplies: N/A

2. Publication Costs/Documentation/Dissemination: N/A

3. Consultant Services:

4. Computer Services: N/A

5. Sub-awards: N/A

6. Other: N/A

H. Total Direct Costs $[redacted]

I. Indirect Costs:

On-campus research at NYU incurs indirect costs at the rate of 58.5% of modified total direct costs (MTDC) for the period beginning 09/01/2014 to 08/30/2017, and provisional thereafter, per the University's Rate Agreement with DHHS, signed 08/19/2014. Per this agreement, modified total direct costs shall exclude equipment, capital expenditures, charges for patient care, student tuition remission, rental costs of off-site facilities, scholarships, and fellowships, as well as the portion of each subgrant or subcontract in excess of $25,000. The amount of indirect costs requested is (b)(4), (b)(6) [redacted]

J. Total Direct and Indirect Costs: $$267,858
K. Residual Funds: None
L. Amount of this request: $267,858
M. Cost Sharing Proposal Level: Not Requested

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Buneo, Christopher Alan	Other agencies(including NSF) to which this proposal has been/will be submitted

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Piper Health Solutions Consortium - Project Account: Intelligent Robotics for Assessing Rehabilitating and Assisting Motor Impairments - Seed Grant

Source of Support:

Total Award Amount: $50,000.00 Total Award Period Covered: 7/1/2013 - 4/30/2017

Location of Project: Arizona State University

Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Neural Correlates of Cooperative Manipulative Actions

Source of Support: AZ DEPT OF HEALTH SERVICES

Total Award Amount: $100,000.00 Total Award Period Covered: 10/23/2014 - 10/22/2015

Location of Project: Arizona State University

Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: (b)(4), (b)(6) [redacted]

Source of Support:

Total Award Amount:

Location of Project:

Person-Months Per Ye

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network (THIS PROPOSAL)

Source of Support: NSF

Total Award Amount: (b) (4) [redacted] Total Award Period Covered: 5/1/2016 – 4/30/2021

Location of Project: Arizona State University

Person-Months Per Year Committed to the Project. Ca (b)(4), (b)(6) [redacted]

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*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding Period.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Bijan Pesaran

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Multiple spatial representations during visually-guided behavior

Source of Support: NIH

Total Award Amount: $736,843 Total Award Period Covered: 8/1/14 – 7/31/18

Location of Project: New York University

Person-Months Per Year Committed to the Project. Ca (b)(4), (b)(6) [redacted]

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Ti (b)(4), (b)(6) [redacted]

Source of Support:

Total Award Amou

Location of Project

Person-Months Pe

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Unlearning neural systems dysfunction in neuropsychiatric disorders

Source of Support: DARPA

Total Award Amount: $847,288 Total Award Period Covered: 6/1/14 – 5/31/16

Location of Project: New York University

Person-Months Per Year Committed to the Project. Ca (b)(4), (b)(6) [redacted]

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Large-scale electrophysiological recording and optogenetic control system

Source of Support: NIH/ Gray Matter Research

Total Award Amount: $432,070 Total Award Period Covered: 09/01/2014-8/31/2017

Location of Project: New York University

Person-Months Per Year Committed to the Project. Ca (b)(4), (b)(6) [redacted]

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network

Source of Support: NSF

Total Award Amount: (b)(4), (b)(6) [redacted] Total Award Period Covered: 05/01/2016-04/30/2021

Location of Project: New York University

Person-Months Per Year Committed to the Project. Ca (b)(4), (b)(6) [redacted]

*If this project has previously been funded by another agency, plea [redacted] ely pre-ceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY

55

ASU Resources and Environment

Visuomotor Learning Lab (Buneo)

Animal

The animal lab is located in the basement of the Biodesign Institute B Building (BioB) at Arizona State University and consists of two animal testing rooms (each ~100 sq. ft), one room for experimental preparation and for conducting small veterinary procedures (~250 sq. ft.), and two large rooms for housing the animals (each ~400 sq. ft). All rooms are contained within a larger suite dedicated to non-human primate research that is shared with another PI. The animal housing rooms are in the same separately enclosed area as the laboratories, separated only by a hallway. These rooms contain both individual cages for each animal housed in the group and one play cage per two animals. There is a separate anteroom (50 sq ft) for gowning, and another small room (50 sq ft) for routine medical care such as cleaning of implanted fixtures. The facility is maintained by full-time university staff who are trained vet techs and primatologists. Animals are individually housed at night time, and pair-housed during the day wherever possible.

Surgeries are performed in the AAALAC-approved Surgical Suite located in the basement of BioB. Animal care technicians provided by the Arizona State University Department of Animal Care and Technologies (DACT) are responsible for daily maintenance and care of the animals and holding rooms. In addition, full-time veterinary services are provided by DACT.

Equipment and software

A 96-channel Plexon system, which allows discrimination of up to 4 different neuron action potentials on each channel, is currently used to record neural activity. In addition to accommodating the fixed microelectrode arrays that will be used in the proposed work, the Plexon system can also be interfaced with a 6-channel NaN microelectrode drive unit for driving single electrodes into cortex. Arm movements are monitored using an active LED based motion tracking system (Visualeyze VZ3000, Phoenix Technologies Inc., sampling rate: 250 Hz, spatial resolution: 0.015mm at 1.2m distance). Eye movements are monitored using a remote optical eye tracking system (ASL Inc., sampling rate: 120 Hz, spatial resolution: 0.25 degrees of visual angle). A semi-immersive, periscope-based display system employing 3D monitors (DTI Inc.) is used for displaying 3D virtual visual stimuli. A National Instruments PXI-1033 PXI Chassis is used for interfacing software and hardware.

Custom LabVIEW software is used for experimental control. Vizard software (WorldViz Inc.) is used for generating the virtual reality environment. Data analysis is carried out using NeuroExplorer, Matlab, Chronux, and custom programs written in either C++ or Python.

Computer

The animal laboratory currently contains 6 computers that are used for data acquisition, data storage, data analysis, and for presenting visual stimuli during experiments. In addition to the laboratory computers, the PI and graduate students also currently have one office computer each that can be used for data analyses, word processing and other tasks.

Office

Office space has been provided for the PI and graduate students on the first floor of the Interdisciplinary Science and Technology Building (ISTB1). The PI has a 150 sq ft. office in ISTB1 and students have 6 feet of desk space and two cabinets in a student bullpen adjacent to the PIs office. Additional desk space exists in the laboratory space for undergraduate students.

Other

Excellent support services are available to the PI at ASU. The School of Biological and Health Systems Engineeering provides secretarial support and the Fulton School of Engineering provides computer support. In addition, ASU maintains a fully staffed machine and electronics shop.

Facilities and Other Resources

Laboratory:

A new laboratory was constructed in 2006 for Dr Pesaran at the Washington Square Campus of New York University. The laboratory occupies approx. 1250 sq ft. The lab consists of a centrally located general work area/meeting room, three experimental setups for behavioral electrophysiology with non-human primates and workbenches for electronics and machining. All facilities are in adjacent rooms. Each experimental setup features a 7' x 7' doubly electrically isolated recording enclosure (ETS Lindgren, IL) constructed from Si steel and copper that provides electromagnetic shielding even at frequencies below 100 Hz.

All experimental setups feature a real-time behavioral control workstation (National Instruments (NI), TX) and a Linux data acquisition PC containing an A/D card (NI, TX). The setups are equipped to monitor and control eye movements and arm movements. Eye movements are monitored using a video tracking system (I-Scan, MA). Hand touch position is monitored using an acoustic touch screen (ELO Touch Systems, CA) mounted in front of a computer display. Two experimental setups are also equipped with motion-capture systems that can track the configuration of the arm and hand in space. One system is a 4-camera system (Phasespace, CA) that tracks infra-red LEDs are embedded in a custom made glove and sleeve the monkeys wear that covers the arm and hand. Another system is a 26-camera system (Motion Analysis, CA) that tracks retroreflective markers that are placed on bone segments. Two proximity sensors are mounted in the primate chair housing. The proximity sensors allow us to constrain either or both hands to be within a 1 cm region near the monkey, letting us control which arm is being used to reach. An additional facility featuring a 16-camera system (Motion Analysis, CA) is currently being installed in a plastic custom animal housing to permit in-cage tracking and wireless recording, see below.

All three experimental setups contain large-scale neurophysiology equipment for multielectrode recordings. Two setups is equipped with the NSpike amplifier system (HIL, MA) which can simultaneously record from up to 127 electrodes and includes 16 DSPs that can perform flexible online filtering and signal processing. One setup is equipped with a 256-channel NSpike amplifier system. We pass the signals from the electrodes through four or eight 32-channel headstages (Multichannel Systems, Germany and Blackrock Microelectronics, UT) before passing them to the NSpike system. A 96-channel wireless system (Blackrock) can perform acquisition in-cage with four antennas. A 1024-channel system is being integrated for massive electrophysiological recordings. A software engineer in the lab has finished development of a data acquisition software package customized for our needs. This package acquires the digitized data (30 kHz per channel) from these DSPs over a local Ethernet. Neural signals are synchronized with all the behavioral signals and processed in a set of circular buffers residing in shared memory. We can process these signals in Matlab (Mathworks, MA) using a set of MEX functions to access these shared memory buffers for online visualizations of behavioral and neural recordings. This set up also includes several different microdrive systems to allow neuronal recordings. One system is an 8-channel motorized microdrive (Alpha Omega, Israel) that allows acute, daily recordings. The other systems are 32-channel, 96-channel and 140-channel microdrives (Gray Matter Research, MT) that are not motorized but allows each electrode to be manually positioned using a lead screw. We have been successful in getting all systems working in the lab and recording spiking and LFP activity on multiple electrodes and have published several papers with these techniques.

Clinical: Not applicable.

Animal:

The University maintains an Institutional Animal Care and Use Committee (IACUC) that reviews all experimental protocols involving animals. The animal facilities are accredited by AAALAC and the physical plant construction, as well as the procedures for animal maintenance, husbandry, and transportation, are in compliance with the laboratory Animal Welfare Act and guidelines stipulated by NIH for the use of animals in experimental research. A university veterinarian is available to help and advise with surgeries and techniques involving animals. A state of the art primate facility houses animals used in the proposed experiments. The facility includes holding rooms for nonhuman primates, procedure rooms, a veterinary staff office, and a fully-equipped surgical suite with prep room and the Brainsight image-guided surgical workstation (Rogue Research, Canada), high-definition video acquisition from the surgical microscope (De Wild), high-definition video acquisition from a surgical exoscope (VITOM) both displayed on a 51” surgical display, and a neurosurgical irrigation and bipolar cautery (Aesculap).

Computer:

The Pesaran laboratory presently has 27 PCs and Macs for stimulus presentation, behavioral control, data acquisition and analysis and word processing. There are 4 additional networked attached storage devices containg 60TB of storage each, providing a total of over 300 TB of storage. An additional data storage network provides backup for over 300TB data as well. All computers are networked by a Gigabit ethernet managed by NYU Information Technology Services. A private 10 Gigabit ethernet network provides 1GB/s network access to the data storage cluster and the computational cluster. These machines are dedicated to other projects supported by the lab. An additional computer will be dedicated to work on this project.

Office:

The Center for Neural Science provides office space for faculty, postdocs, students and administrators. The Center also provides shared office support for poster printing and scanning.

Other resources:

The NYU Center for Neural Science is a stimulating environment for conducting research on problems related to brain function. A regular seminar series hosts internationally-reknowned speakers and Annual symposia are hosted at the Center. Through the psychology and physics departments, electronics and machine shop services are available at reasonable rates. MRI services are provided by the Center for Brain Imaging. MRI services include access to a full-time MR physicist and radiology technician and programmer. The Center for Brain Imaging has secured funding for a renovation to install a new Siemens Prisma 3T scanner in 2015 which will be in place for the research proposed for this submission. Histological services are available through a shared facility containing an Olympus VS120, a vibratome, centrifuge and freezer facilities.

Data Management Plan

Intellectual property and data generated under this project will be administered in accordance with Arizona State University (ASU), New York University (NYU), and NSF Data Management Guidelines. All members of the research team will receive instruction in the Responsible Conduct of Research (RCR).

Data Products

The proposed work will produce procedural, descriptive, and experimental data related to non-human primate neurophysiological and psychophysical tasks. Data will be collected using the instruments and methods described in the proposal. The proposed research will produce raw data from motion capture systems and cortical recordings, code for collection and interpretation of kinematic, psychophysical and neurophysiological data, photographs and videos of the experiments, theory and simulations, statistical analyses, and numerical algorithms. Raw kinematic data will be post-processed and used for understanding the behavioral correlates of multimodal integration. Raw cortical recording data will be post-processed and used to establish principles of multimodal integration in the cortex.

The Education Goals will produce hands-on instructional modules for elementary school students, currricular materials (lecture notes, handouts, examples, demonstrations) for undergraduate- and graduate-level courses, and experimental data from undergraduate internships.

Data Storage and Sharing (across labs comprising the research team)

All laboratory procedures, observations, and results will be initially documented in laboratory notebooks and computers located in each investigator's locked lab. Custom code will be archived and documented using an account and repository running under TortoiseSVN, a freely available revision control/version control/source control software developed for Windows. Collaborative documents, experimental protocols, and raw data will be shared across labs using secure, shared network drives. The shared drives will be backed up nightly to a secure internal RAID network attached storage (NAS) system. The NAS system will be further backed up nightly to a secure mirrored RAID NAS system in a different building on each campus. We have budgeted for computer equipment and software resources to build data servers at both ASU and NYU. The data servers will include a secure, network box and permanent fixed storage in RAID arrays in Buneo's and Pesaran's labs. In addition to providing a resource for data archiving, this data storage system will also provide team members access to data, software, and ongoing efforts at publication which span the interdisciplinary team.

Data will be retained for at least three years beyond the award period, as required by NSF guidelines. In the event that discoveries or inventions are made in direct connection with this data, access will be granted upon request once appropriate invention disclosures and/or provisional patent filings are made. Key data relevant to the discovery will be preserved until all issues of intellectual property are resolved. The data acquired and preserved in the context of this proposal will be further governed by ASU and NYU policies pertaining to intellectual property, record retention, and data management.

Dissemination

Data dissemination to the scientific community will occur primarily through podium and poster presentations at relevant, high-impact scientific meetings and long-term publication in archival conference proceedings, peer-reviewed publications, and academic theses. The proposed work lends itself to dissemination at a variety of scientific meetings, including the Annual Meetings of the Society for Neuroscience and Society for Neural Control of Movement, Computational and Systems Neuroscience (Cosyne), and the Annual International Conference of the IEEE Engineering in Medicine and Biology Society. Procedures, methodologies, and results of general interest will be photo- and/or video-documented and published separately in open-access format.

Each investigator's existing, open-access lab webpage will accommodate an introduction to the ongoing research with links to online versions of research publications and NSF's official webpage detailing the award. If requested, data and custom code will be made available for sharing to qualified parties by the research team so long as such a request does not compromise intellectual property interests, interfere with publication, invade subject privacy, or betray confidentiality. Hands-on instructional modules developed as part of the proposed educational objectives will be given to local elementary school teachers. Instructional videos will also be posted to ASU's "Science is Fun" video repository for public access. Curricular materials (lecture notes, handouts, examples, demonstrations) for undergraduate- and graduate-level courses will be disseminated in the process of instruction. Demonstrations of general interest will be posted to open-access webpages.

Other sensitive issues

In the event that discoveries or inventions are made in direct connection with this work, they will be submitted to the intellectual property offices at ASU and/or NYU.

Postdoctoral Researcher Mentoring Plan

We are requesting support for one postdoctoral trainee. The PI and the Co-I will co-mentor the postdoctoral trainee. Postdoctoral mentoring will consist of regular meetings between the PI, Co-I and the postdoctoral trainee, conducted via Skype or conference call. In addition, the PI and Co-I have budgeted for one trip per year to the Co-I's home institution, to work closely with the Co-I on advanced techniques for data processing and analysis. The PI will hold also hold weekly lab meetings to discuss experimental design, pilot data collection, data processing and analyses, and manuscript preparation. All members of the PI's lab will attend these meetings in order to foster cross-fertilization of ideas as well as to train the postdoctoral trainee in giving oral presentations.

Career counseling is an important component of postdoctoral training. Besides regular and informal discussions about career opportunities in the field, the PI will encourage participation in professional workshops at ASU and international conferences for exploring career opportunities in academia and industry.

The PI has significant experience with preparation of grant proposals, publications, and presentations. He will train the postdoctoral trainee in scientific writing by requiring regular written reports, submissions to peer-reviewed archival journals, and oral presentations at national and international meetings. The ability to write grants is also a very important skill in academia. The PI will therefore train the postdoctoral trainee in writing proposals for postdoctoral fellowships and in contributing to the preparation of grant proposals with the PI. The PI will ensure that the postdoctoral trainee is given regular feedback so that they acquire confidence, independence, and the skills necessary to write competitive grant proposals.

The PI recognizes the importance of mentoring postdoctoral trainees in becoming effective teachers before they become tenure track faculty. He will therefore involve the postdoctoral trainee in teaching lectures in his undergraduate and graduate courses (e.g., Human Systems Neuroscience) including laboratories. The PI will help the postdoctoral trainee in preparing lectures and will also attend the lectures and provide feedback. The postdoctoral trainee will also work closely with and co-mentor graduate students working on related studies.

The PI is part of a research team at ASU that is highly interdisciplinary in terms of expertise and research backgrounds. Regular interactions among the investigators in this team through joint lab meetings, journal clubs, and other venues will expose the postdoctoral trainee to different theoretical issues in the field as well as complementary experimental approaches. Similarly, the PI has other collaborators both at ASU and other institutions. This network of collaborators will further expose the postdoctoral trainee to a wide range of research problems and techniques.

ASU is very active in the area of bioethics. There are active faculty driving bioethics programs in the Fulton Schools of Engineering, the School of Life Sciences, the Sandra Day O'Connor College of Law, and the Consortium for Science, Policy, & Outcomes. In particular the PI has interacted with the bioethics group in the Center for Biology and Society in the School of Life Sciences. Through this interaction he has taught a course ("Neural Transhumanism") which focused on ethics in neural engineering, selection of animal models in biomedical research, and the ramifications of rapidly developing neural technologies. The PI is also active in exploring means for enhancing the productivity of interactions between bioethicists and researchers in science and engineering. As a result the post-doctoral trainee will be required to devote a portion of their time to assisting with efforts to improve these interactions. Finally, the postdoctoral trainee will also receive routine instruction in the Responsible Conduct of Research, the Protection of Human Subjects, and Institutional Review Board policies.

Institutional Animal Care and Use Committee (IACUC)
Office of Research Integrity and Assurance
Arizona State University
660 South Mill Avenue, Suite 315
Tempe, Arizona 85287-6111
Phone: (480) 965-4387 *FAX:* (480) 965-7772

Animal Protocol Review

ASU Protocol Number:	**15-1429R Amendment #1**
Old Protocol Title:	**Cortical Mechanisms of Sensorimotor Integration**
New Protocol Title:	**Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
Principal Investigator:	**Christopher Buneo**
Date of Action:	**6/16/2016**

The animal protocol review was considered by the Committee and the following decisions were made:

The amendment was administratively approved to change the title of the protocol and add a funding source.

If you have not already done so, documentation of Level III Training (i.e., procedure-specific training) will need to be provided to the IACUC office before participants can perform procedures independently. For more information on Level III requirements see https://researchintegrity.asu.edu/training/animals/levelthree.

Total # of Animals:	**6**	
Species:	**NHP**	**Pain Level: D**

Protocol Approval Period: **4/23/2015 – 4/22/2018**

Sponsor:	**NSF**
ASU Proposal/Award #:	**FP00004593**
Title:	**Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**

Signature: Augustowski for C Johnson
IACUC Chair or Designee

Date: 6/16/2016

Cc: IACUC Office
IACUC Chair

ARIZONA STATE UNIVERSITY

Institutional Animal Care and Use Committee

REQUEST FOR CHANGES TO AN APPROVED PROTOCOL

Protocol No. 15-1429R
Previous Title: Cortical Mechanisms of Sensorimotor Integration
New Title: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network
Principal Investigator: Christopher Buneo Email Address: cbuneo@asu.edu
If not PI, whom should we contact for questions related to this amendment: Rachele McAndrew Email Address: rmcandrew@asu.edu

Requested Change (check all that apply):

☐ New procedures to be performed – complete Part A and sign assurance.
☐ New species and or an increase in the number of animals to be used – complete Part A and sign assurance.
☐ New location of housing or procedures – complete Part A and sign assurance.
☐ New personnel – complete Part B and sign assurance.
☒ Other – complete Part A and sign assurance.

A. Description of Requested Changes
For new procedures or additional animals, list the **Category of Pain.**
If you are adding a procedure that could create pain or distress, you need to include a **literature search** for alternatives.
If you are requesting an increase in animal numbers, provide justification with supportive statistics.
Describe the changes you are requesting. We are requesting to change the title of this protocol in order to corresepond to the grant that will be funding this work. The new title will be "Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network". The funding agency is the National Science Foundation (NSF), proposal number FP00004593.

B. Addition of Personnel

Name	Title	ASURITE name	Role in Protocol (What procedures will each person be doing under supervision?)	What procedures will each person be doing independently (without supervision)?	Species with which individual will have direct contact ("all" or list species)*	IACUC USE ONLY Training (mm/yy)

For each individual, describe the individual's training and years of experience with all listed species and procedures they will be conducting under this protocol. For procedures for which they are not yet trained, but will likely be trained to do during the activity period of this protocol, provide a description of who will provide such training:

Assurance
As Principal Investigator of this protocol, I assure that all procedures will be conducted as described in this amendment and that personnel will receive appropriate additional training prior to conducting any new procedures that are not listed above.

SIGNED:
Christopher Buneo 6/15/2016
Principal Investigator Date

For IACUC use only:
☒ Administratively approved - Approving administrator: S. Augustowski Date of approval: 6/16/2016
☐ Administratively handled by VCV - Veterinarian providing verification: Date of verification:
Sources used for verification:
☐ Approved by Designated Review – Designated reviewer: Date of approval:

☐ Approved by Full Committee Review – Primary reviewer: Date of approval:

NATIONAL SCIENCE FOUNDATION

Diary Note

Proposal:1557886 **PI Name:**Pesaran, Bijan

Name: Edda Thiels
Date: 07/26/2016 06:32 PM
Keyword: IACUC approval
Note:
All of the vertebrate animal work conducted under this award will be carried out at the lead institution (Arizona State University). No vertebrate animal work will be carried out at the non-lead institution (NYU).

SUMMARY PROPOSAL BUDGET

YEAR 1

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Arizona State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Christopher Buneo

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)

NSF Funded Person-months: CAL | ACAD | SUMR — Funds Requested By proposer — Funds granted by NSF (if different)

(b) (4) [redacted]

1. **Christopher A Buneo - Principal Investigator**
2.
3.
4.
5.
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)

B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)
1. (**1**) POST DOCTORAL SCHOLARS
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)
3. (**3**) GRADUATE STUDENTS
4. (**0**) UNDERGRADUATE STUDENTS
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)
6. (**0**) OTHER

TOTAL SALARIES AND WAGES (A + B)

C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)

TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)

D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE

Data server
Plexon Data Acquisition System
Virtual Reality Training Platform

TOTAL EQUIPMENT

E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)
2. INTERNATIONAL

F. PARTICIPANT SUPPORT COSTS
1. STIPENDS $ **0**
2. TRAVEL **0**
3. SUBSISTENCE **0**
4. OTHER **0**

TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PA

G. OTHER DIRECT COSTS
1. MATERIALS AND SUPPLIES
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION
3. CONSULTANT SERVICES
4. COMPUTER SERVICES
5. SUBAWARDS
6. OTHER

TOTAL OTHER DIRECT COSTS

H. TOTAL DIRECT COSTS (A THROUGH G)

I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)
Salary/Travel/Supplies (Rate: 54.5000, Base (b)(4) [redacted]

TOTAL INDIRECT COSTS (F&A)

J. TOTAL DIRECT AND INDIRECT COSTS (H + I)

K. SMALL BUSINESS FEE

L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Christopher Buneo

ORG. REP. NAME*
Lindsey bosak

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

1 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

Revised Proposal Budget Revision # 1 for 1558151 Submitted On Jun 27 2016 12:09PM Electronic Signature

SUMMARY PROPOSAL BUDGET

YEAR 2

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Arizona State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Christopher Buneo

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b)(4) [redacted]		
2.			
3.			
4.			
5.			
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE			
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)			
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (**1**) POST DOCTORAL SCHOLARS			
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)			
3. (**0**) GRADUATE STUDENTS			
4. (**0**) UNDERGRADUATE STUDENTS			
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)			
6. (**0**) OTHER			
TOTAL SALARIES AND WAGES (A + B)			
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)			
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)			
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE			
TOTAL EQUIPMENT			
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)			
2. INTERNATIONAL			
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS $ **0**			
2. TRAVEL **0**			
3. SUBSISTENCE **0**			
4. OTHER **0**			
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PA			
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES			
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION			
3. CONSULTANT SERVICES			
4. COMPUTER SERVICES			
5. SUBAWARDS			
6. OTHER			
TOTAL OTHER DIRECT COSTS			
H. TOTAL DIRECT COSTS (A THROUGH G)			
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base:** (b)(4) [redacted]			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)			
K. SMALL BUSINESS FEE			
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)			

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Christopher Buneo

ORG. REP. NAME*
Lindsey bosak

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

2 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET YEAR 3

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Arizona State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Christopher Buneo

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1.	(b) (4) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE					
TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)					
2. INTERNATIONAL					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ **0**					
2. TRAVEL **0**					
3. SUBSISTENCE **0**					
4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PA					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER					
TOTAL OTHER DIRECT COSTS					
H. TOTAL DIRECT COSTS (A THROUGH G)					
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **(Rate: , Base:)**					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					
K. SMALL BUSINESS FEE					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)					

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Christopher Buneo

ORG. REP. NAME*
Lindsey bosak

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

3 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

YEAR 4

ORGANIZATION **Arizona State University**	**FOR NSF USE ONLY** PROPOSAL NO.	DURATION (months) Proposed | Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**	AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL | ACAD | SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	[redacted]		
2.			
3.			
4.			
5.			
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE			
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)			
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (**1**) POST DOCTORAL SCHOLARS			
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)			
3. (**0**) GRADUATE STUDENTS			
4. (**0**) UNDERGRADUATE STUDENTS			
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)			
6. (**0**) OTHER			
TOTAL SALARIES AND WAGES (A + B)			
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)			
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)			
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE			
TOTAL EQUIPMENT			
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)			
2. INTERNATIONAL			
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS $ **0**			
2. TRAVEL **0**			
3. SUBSISTENCE **0**			
4. OTHER **0**			
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PA			
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES			
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION			
3. CONSULTANT SERVICES			
4. COMPUTER SERVICES			
5. SUBAWARDS			
6. OTHER			
TOTAL OTHER DIRECT COSTS			
H. TOTAL DIRECT COSTS (A THROUGH G)			
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base:** [redacted]			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)			
K. SMALL BUSINESS FEE			
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)			
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $		

PI/PD NAME **Christopher Buneo**	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

YEAR 5

ORGANIZATION	FOR NSF USE ONLY		
Arizona State University	PROPOSAL NO.	DURATION (months)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR Christopher Buneo	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Christopher A Buneo - Principal Investigator	(b) (4) [redacted]				
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS					
2. (1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (0) GRADUATE STUDENTS					
4. (0) UNDERGRADUATE STUDENTS					
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (0) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE					
TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)					
2. INTERNATIONAL					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PA					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER					
TOTAL OTHER DIRECT COSTS					
H. TOTAL DIRECT COSTS (A THROUGH G)					
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Salary/Travel/Supplies (Rate: 54.5000, Base: (b) (4) [redacted]					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					
K. SMALL BUSINESS FEE					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)					
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME	FOR NSF USE ONLY		
Christopher Buneo	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG
Lindsey bosak			

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

Cumulative

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Arizona State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Christopher Buneo

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b) (4) [redacted]				
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAG					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**3**) POST DOCTORAL SCHOLARS					
2. (**3**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**3**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE					
TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)					
2. INTERNATIONAL					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ **0**					
2. TRAVEL **0**					
3. SUBSISTENCE **0**					
4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PA					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER					
TOTAL OTHER DIRECT COSTS					
H. TOTAL DIRECT COSTS (A THROUGH G)					
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					
K. SMALL BUSINESS FEE					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)					

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Christopher Buneo

ORG. REP. NAME*
Lindsey bosak

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

Budget Impact Statement

Overall the budget was (b)(4) [redacted] The following changes were necessary to accommodate the new budget:

1) (b) (4) [redacted]
2)
3)
4)
5)
6)

Despite these changes we are confident that all of the experimental work can be realistically completed within five years and without significantly impacting the overall aims of the project.

Budget Justification

A. Senior Personnel

Christopher Buneo, Principal Investigator (b) (4), (b) (6) [redacted] Dr. Buneo will be responsible for leadership and administration of the research project as well the experimental design, data analyses and preparation of the manuscripts. He will also supervise and train one PhD student and co-mentor a postdoctoral fellow with the Co-Investigator.

B. Other Personnel

We request (b)(4) [redacted] for one postdoctoral fellow and one graduate student to work with the investigators on the project. We also request (b)(4) [redacted] for a laboratory coordinator.

Postdoctoral fellow (b)(4) [redacted] The postdoc will be trained to design experimental protocols, acquire data, perform data analyses, prepare oral and written reports for lab meetings and conference presentation, and prepare manuscripts. The postdoc will also help directly supervise the PhD student.

PhD students (b)(4) [redacted] One PhD student is allocated at an effort level of (b)(4) [redacted] per week. The student will be trained to design experimental protocols and perform pilot testing, learn data acquisition and analyses, prepare oral and written reports for lab meetings and conference presentation, and help prepare manuscripts.

(b)(4), (b)(6) [redacted] Laboratory coordinator (b)(4) [redacted] The coordinator will be responsible for managing the non-human primates and providing infrastructure support for the primate lab.

C. Fringe Benefits (Employee Related Expenses)

Arizona State University (a) defines fringe benefits as direct costs, (b) estimates fringe on proposal budgets and (c) charges sponsors using the Federally-approved fringe benefit rate in effect at time salary incurs. The rate agreement is negotiated with the U.S. Department of Health and Human Services. The current agreement, dated May 13, 2016. Fringe Benefits expenses consist of the following types of costs: FICA, Workmen's Compensation, Health Insurances, Retirement Plans, etc. For purposes of proposal budgeting, fringe benefit estimates are calculated as a percent of salary. Benefits are calculated as follows on base salaries:

ERE Rate Estimates	**FACULTY**	**STAFF**	**POST-DOC'S**	**RA/TA**
FY 2017 Estimated Rate	(b)(4) [redacted]			
FY 2018 Estimated Rate				
FY 2019 Estimated Rate				
FY 2020 Estimated Rate				
FY 2021 Estimated Rate				

** A rate o* (b)(4) [redacted] *calation applies for out years beyond 2020*

D. Equipment (Year One $232,000):

Plexon Data Acquisition System	$115,000
Virtual Reality Training Platform (Motion Analysis Tracking System $80,000, Custom 3ds Max Live Characters Plugin $20,000, SIMM (Software for musculoskeletal modeling $7,000)	$107,000
Data server	$10,000
Total	**$232,000**

Funds are requested for a Plexon data acquisition system that will enable recording from three cortical areas simultaneously, a key component of the proposed work. Funds are also requested for the construction of the virtual reality training platform developed by the (b)(4), (b)(6) [redacted] which will enable the visual feedback manipulations that are a cornerstone of the project ($107,000 total). This includes a motion tracking system from Motion Analysis, a custom 3ds Max live characters plugin, and SIMM (Software for Musculoskeletal Modeling). Lastly, funds are requested to build a data server for the research team at ASU ($10,000).

E. Travel

Domestic Travel	Year 1	Year 4
Conference (TBD)	3 Travelers	3 Travelers
Airfare @$500 ea	$1,500	$1,500
Lodging 3 nights@$150	$1,350	$1,350
Per diem 3 days@$70	$630	$630
Ground Trans@$70	$210	$210
Misc. 3 days@$25	$225	$225
Conferences Total	$3,915	$3,915
New York (Postdoc/Stud)	1 Traveler	1 Traveler
Airfare@$500 ea	$500	$500
Lodging 14 nights@$304	$4,256	$4,256
Per diem 14 days@$71	$994	$994
Ground Trans@$100	$100	$100
Misc. 14 days@$25	$350	$350
Postdoc/Student Total	$6,200	$6,200
New York (PI)	1 Traveler	1 Traveler
Airfare@$500	$500	$500
Lodging 3 nights@$304	$912	$912
Per diem 3 days@$71	$213	$213
Ground Trans@$100	$100	$100
Misc. 3 days@$25	$75	$75
PI New York Trip	$1,800	$1,800
Washington, DC (Student)	1 Traveler	1 Traveler
Airfare@$450	$450	$450
All inclusive $4,000	$4,000	$4,000
Misc/13 days@$25 per day	$325	$325
Total Washington DC	$4,775	$4,775
Total domestic travel	$16,690	$16,690
Foreign Travel (TBD)	1 Traveler	1 Traveler
Airfare@$1,500	$1,500	$1,500
Lodging 5 nights@$200	$1,000	$1,000
Per diem 6 days@$100	$600	$600
Ground Trans@$200	$200	$200
Misc. 6 days@$50	$300	$300
Total Foreign Travel	$3,600	$3,600

We have requested support for the PI (1 domestic meeting in years 1 and 4; 1 international meeting in years 1 and 4) and two trainees (Postdoc and PhD student; 1 domestic meeting in years 1 and 4) to attend high-impact scientific meetings such the Annual Meetings of the Society for Neuroscience and Society for Neural Control of Movement or the Computational and Systems Neuroscience (Cosyne) to present findings generated by this project. We have also requested support for the PI (1 trip years 1 and 4) and either the postdoctoral fellow or PhD student (1 trip years 1 and 4) to visit the Co-Investigator's institution to discuss research findings. In the case of the postdoc/student, this trip will be an immersive 2-week experience which will also involve hands-on instruction from the Co-Investigator (Pesaran) on advanced data analysis techniques relevant to the project. Lastly, as an additional training opportunity, funds have been requested for a graduate student to attend *Science Outside the Lab*, hosted by ASU's Consortium for Science, Policy & Outcomes (CSPO), an immersive training experience which explores the relationships among science, policy, and societal outcomes in Washington, D.C.

Note: The travel budget was estimated in accordance with the University's travel policy (see http://www.asu.edu/aad/manuals/fin/index.html#500) based on current air fares, current ASU authorized per diem rates (http://www.gao.az.gov/publications/SAAM/Supp_I_trvrates-012308.pdf), airport shuttle services, and, if applicable, conference registration fees and/or car rental.

G. Other Direct Costs

Surgical and General Materials and Supplies: Funds are requested for surgery related expenses and other materials and supplies necessary for the successful completion of the proposed work.

	Year 1	Year 2	Year 3	Year 4	Year 5
Rhesus macaque monkeys 4@$6,000 ea	$24,000	$0	$0	$0	$0
Animal maintenance	$23,952	$23,952	$0	$18,952	$15,047
Computers 2@$3,000	$6,000	$0	$0	$0	$0
Materials	$21,444	$14,198	$0	$6,290	$0
Equipment maintenance	$5,000	$5,000	$0	$5,000	$0
Total	**$80,396**	**$43,150**	**$0**	**$30,242**	**$15,047**

These expenses include animal purchases (2 Rhesus macaque monkeys in year 1; $24,000 total including transportation costs), computers (2 in year 1; $6000 total), animal per diems (years 1-2,4-5; $81,903 total), microelectrode arrays (3 in years 1 and 2; $24,000 total), supplies for implantation and maintenance of the arrays, fixation pedestals, and associated hardware ($10,000 years 1-5), and materials and supplies for maintenance of primate chairs and testing apparatus ($7,932 in years 1-5).

Publication costs: Funds are requested ($6,250 total) to support publications in high impact factor journals such as *Nature Neuroscience, Neuron, Journal of Neuroscience and Journal of Neurophysiology*.

Tuition Remission: The tuition charge for the graduate students is $16,831 for YR-1 and an 8% escalation rate on tuition for years beyond FY-17. Tuition for the graduate student is included as a mandatory benefit and is charged in proportion to the amount of effort the graduate student will work on the project. Tuition charges are exempt from Facilities & Administrative costs.

Type of Application	Period of Support	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021 and beyond
New and Renewal*	AY	$14,632	$15,803	$17,067	$18,432	$19,907	Escalate tuition at 8% per year
New and Renewal*	Summer	$ 952	$ 1,028	$ 1,110	$ 1,199	$ 1,295	
	Total	$15,584	$16,831	$18,177	$19,631	$21,202	

H. Facilities and Administration (F&A) Costs

Indirect costs were calculated on Modified Total Direct Costs (MTDC) using F&A rates approved by the U.S. Department of Health and Human Services. The current rate for projects like the one proposed here, organized research, is 54.5% for FY17. The most current rate agreement is dated May 13, 2016. Items excluded from F&A calculation include: capital equipment, subcontracts over the first $25,000, a portion of the student tuition remission, participant support, rental/maintenance of off-campus space, and patient care fees.

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION **Arizona State University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b) (4), (b) (6) [redacted]		
2.			
3.			
4.			
5.			
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE			
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)			
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (**1**) POST DOCTORAL SCHOLARS			
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)			
3. (**3**) GRADUATE STUDENTS			
4. (**0**) UNDERGRADUATE STUDENTS			
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)			
6. (**0**) OTHER			
TOTAL SALARIES AND WAGES (A + B)			
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)			
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)			
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)			
Data server	$ **10,000**		
Plexon Data Acquisition System	**115,000**		
Virtual Reality Training Platform	**107,000**		
TOTAL EQUIPMENT		**232,000**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)		**16,690**	
2. INTERNATIONAL		**3,600**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**			
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS		**0**	
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		**80,396**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		**1,250**	
3. CONSULTANT SERVICES		**0**	
4. COMPUTER SERVICES		**0**	
5. SUBAWARDS		**0**	
6. OTHER		**46,752**	
TOTAL OTHER DIRECT COSTS		**128,398**	
H. TOTAL DIRECT COSTS (A THROUGH G)		(b)(4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base:** (b)(4) [redacted] TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)		**721,492**	
K. SMALL BUSINESS FEE		**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)		**721,492**	
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $		

PI/PD NAME **Christopher Buneo**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

Revised Proposal Budget Revision # 2 for 1558151 Submitted On Jul 13 2016 10:39AM Electronic Signature

SUMMARY PROPOSAL BUDGET

YEAR 2

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Arizona State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Christopher Buneo

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b) (4), (b) (6) [redacted]		
2.			
3.			
4.			
5.			
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE			
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)			
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (**1**) POST DOCTORAL SCHOLARS			
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)			
3. (**0**) GRADUATE STUDENTS			
4. (**0**) UNDERGRADUATE STUDENTS			
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)			
6. (**0**) OTHER			
TOTAL SALARIES AND WAGES (A + B)			
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)			
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)			
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)			
TOTAL EQUIPMENT		**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)		**0**	
2. INTERNATIONAL		**0**	
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS $ **0**			
2. TRAVEL **0**			
3. SUBSISTENCE **0**			
4. OTHER **0**			
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS		**0**	
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		**43,150**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		**1,250**	
3. CONSULTANT SERVICES		**0**	
4. COMPUTER SERVICES		**0**	
5. SUBAWARDS		**0**	
6. OTHER		**0**	
TOTAL OTHER DIRECT COSTS		**44,400**	
H. TOTAL DIRECT COSTS (A THROUGH G)		(b)(4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base:** (b)(4) [redacted]			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)		**200,000**	
K. SMALL BUSINESS FEE		**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)		**200,000**	
M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $			

PI/PD NAME
Christopher Buneo

ORG. REP. NAME*
Lindsey bosak

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 3

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Arizona State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Christopher Buneo

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1.	0.00	0.00	0.00		
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (0) GRADUATE STUDENTS				0	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				0	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				0	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				0	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				0	
2. INTERNATIONAL				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				0	
H. TOTAL DIRECT COSTS (A THROUGH G)				0	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **(Rate: , Base:)**					
TOTAL INDIRECT COSTS (F&A)				0	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				0	
K. SMALL BUSINESS FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				0	

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Christopher Buneo

ORG. REP. NAME*
Lindsey bosak

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET YEAR 4

ORGANIZATION **Arizona State University**			FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**			AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL ACAD SUMR		Funds Requested By proposer		Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b) (4), (b) (6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**1**) POST DOCTORAL SCHOLARS					
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEE					
TOTAL EQUIPMENT			**0**		
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)			**16,690**		
2. INTERNATIONAL			**3,600**		
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS			**0**		
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES			**30,242**		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION			**3,750**		
3. CONSULTANT SERVICES			**0**		
4. COMPUTER SERVICES			**0**		
5. SUBAWARDS			**0**		
6. OTHER			**0**		
TOTAL OTHER DIRECT COSTS			**33,992**		
H. TOTAL DIRECT COSTS (A THROUGH G)			(b)(4) [redacted]		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base:** (b)(4) [redacted] TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)			**250,000**		
K. SMALL BUSINESS FEE			**0**		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)			**250,000**		
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $				
PI/PD NAME **Christopher Buneo**			FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey bosak**			Date Checked	Date Of Rate Sheet	Initials - ORG

4 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 5

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months) Proposed	Granted
AWARD NO.		

ORGANIZATION
Arizona State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Christopher Buneo

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b) (4), (b) (6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEED					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**0**	
2. INTERNATIONAL				**0**	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ **0**					
2. TRAVEL **0**					
3. SUBSISTENCE **0**					
4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**15,047**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**0**	
TOTAL OTHER DIRECT COSTS				**15,047**	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b)(4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Salary/Travel/Supplies (Rate: 54.5000, Base:** (b)(4) [redacted]					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**100,000**	
K. SMALL BUSINESS FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**100,000**	

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Christopher Buneo

ORG. REP. NAME*
Lindsey bosak

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

5 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION **Arizona State University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Christopher Buneo**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Christopher A Buneo - Principal Investigator**	(b)(4) [redacted]		
2.			
3.			
4.			
5.			
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE			
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)			
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (**3**) POST DOCTORAL SCHOLARS			
2. (**3**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)			
3. (**3**) GRADUATE STUDENTS			
4. (**0**) UNDERGRADUATE STUDENTS			
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)			
6. (**0**) OTHER			
TOTAL SALARIES AND WAGES (A + B)			
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)			
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)			
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)	$ **232,000**		
TOTAL EQUIPMENT		**232,000**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)		**33,380**	
2. INTERNATIONAL		**7,200**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**			
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS		**0**	
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		**168,835**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		**6,250**	
3. CONSULTANT SERVICES		**0**	
4. COMPUTER SERVICES		**0**	
5. SUBAWARDS		**0**	
6. OTHER		**46,752**	
TOTAL OTHER DIRECT COSTS		**221,837**	
H. TOTAL DIRECT COSTS (A THROUGH G)		(b)(4) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)		**1,271,492**	
K. SMALL BUSINESS FEE		**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)		**1,271,492**	
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $		

PI/PD NAME **Christopher Buneo**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Lindsey bosak**	Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

Budget Impact Statement

Overall the budget was (b)(4) [redacted] The following changes were necessary to accommodate the new budget:

1) (b)(4) [redacted]
2)
3)
4)
5)
6)

Despite these changes we are confident that all of the experimental work can be realistically completed within five years and without significantly impacting the overall aims of the project.

Budget Justification

A. Senior Personnel
Christopher Buneo, Principal Investigator [redacted] Dr. Buneo will be responsible for leadership and administration of the research project as well the experimental design, data analyses and preparation of the manuscripts. He will also supervise and train one PhD student and co-mentor a postdoctoral fellow with the Co-Investigator.
B. Other Personnel
We request [redacted] for one postdoctoral fellow and one graduate student to work with the investigators on the project. We also request [redacted] for a laboratory coordinator.
Postdoctoral fellow ([redacted]): The postdoc will be trained to design experimental protocols, acquire data, perform data analyses, prepare oral and written reports for lab meetings and conference presentation, and prepare manuscripts. The postdoc will also help directly supervise the PhD student.
PhD students [redacted]): One PhD student is allocated at an effort level of [redacted] week. The student will be trained to design experimental protocols and perform pilot testing, learn data acquisition and analyses, prepare oral and written reports for lab meetings and conference presentation, and help prepare manuscripts.
[redacted] Laboratory coordinator [redacted]): The coordinator will be responsible for managing the non-human primates and providing infrastructure support for the primate lab.

C. Fringe Benefits (Employee Related Expenses)
Arizona State University (a) defines fringe benefits as direct costs, (b) estimates fringe on proposal budgets and (c) charges sponsors using the Federally-approved fringe benefit rate in effect at time salary incurs. The rate agreement is negotiated with the U.S. Department of Health and Human Services. The current agreement, dated May 13, 2016. Fringe Benefits expenses consist of the following types of costs: FICA, Workmen's Compensation, Health Insurances, Retirement Plans, etc. For purposes of proposal budgeting, fringe benefit estimates are calculated as a percent of salary. Benefits are calculated as follows on base salaries:

ERE Rate Estimates	**FACULTY**	**STAFF**	**POST-DOC'S**	**RA/TA**
FY 2017 Estimated Rate	[redacted]			
FY 2018 Estimated Rate				
FY 2019 Estimated Rate				
FY 2020 Estimated Rate				
FY 2021 Estimated Rate				

** A rate o[redacted]scalation applies for out years beyond 2020*

D. Equipment (Year One $232,000):

Plexon Data Acquisition System	$115,000
Virtual Reality Training Platform (Motion Analysis Tracking System $80,000, Custom 3ds Max Live Characters Plugin $20,000, SIMM (Software for musculoskeletal modeling $7,000)	$107,000
Data server	$10,000
Total	**$232,000**

Funds are requested for a Plexon data acquisition system that will enable recording from three cortical areas simultaneously, a key component of the proposed work. Funds are also requested for the construction of the virtual reality training platform developed by the [redacted] which will enable the visual feedback manipulations that are a cornerstone of the project ($107,000 total). This includes a motion tracking system from Motion Analysis, a custom 3ds Max live characters plugin, and SIMM (Software for Musculoskeletal Modeling). Lastly, funds are requested to build a data server for the research team at ASU ($10,000).

E. Travel

Domestic Travel	Year 1	Year 4
Conference (TBD)	3 Travelers	3 Travelers
Airfare @$500 ea	$1,500	$1,500
Lodging 3 nights@$150	$1,350	$1,350
Per diem 3 days@$70	$630	$630
Ground Trans@$70	$210	$210
Misc. 3 days@$25	$225	$225
Conferences Total	$3,915	$3,915
New York (Postdoc/Stud)	1 Traveler	1 Traveler
Airfare@$500 ea	$500	$500
Lodging 14 nights@$304	$4,256	$4,256
Per diem 14 days@$71	$994	$994
Ground Trans@$100	$100	$100
Misc. 14 days@$25	$350	$350
Postdoc/Student Total	$6,200	$6,200
New York (PI)	1 Traveler	1 Traveler
Airfare@$500	$500	$500
Lodging 3 nights@$304	$912	$912
Per diem 3 days@$71	$213	$213
Ground Trans@$100	$100	$100
Misc. 3 days@$25	$75	$75
PI New York Trip	$1,800	$1,800
Washington, DC (Student)	1 Traveler	1 Traveler
Airfare@$450	$450	$450
All inclusive $4,000	$4,000	$4,000
Misc/13 days@$25 per day	$325	$325
Total Washington DC	$4,775	$4,775
Total domestic travel	$16,690	$16,690
Foreign Travel (TBD)	1 Traveler	1 Traveler
Airfare@$1,500	$1,500	$1,500
Lodging 5 nights@$200	$1,000	$1,000
Per diem 6 days@$100	$600	$600
Ground Trans@$200	$200	$200
Misc. 6 days@$50	$300	$300
Total Foreign Travel	$3,600	$3,600

We have requested support for the PI (1 domestic meeting in years 1 and 4; 1 international meeting in years 1 and 4) and two trainees (Postdoc and PhD student; 1 domestic meeting in years 1 and 4) to attend high-impact scientific meetings such the Annual Meetings of the Society for Neuroscience and Society for Neural Control of Movement or the Computational and Systems Neuroscience (Cosyne) to present findings generated by this project. We have also requested support for the PI (1 trip years 1 and 4) and either the postdoctoral fellow or PhD student (1 trip years 1 and 4) to visit the Co-Investigator's institution to discuss research findings. In the case of the postdoc/student, this trip will be an immersive 2-week experience which will also involve hands-on instruction from the Co-Investigator (Pesaran) on advanced data analysis techniques relevant to the project. Lastly, as an additional training opportunity, funds have been requested for a graduate student to attend *Science Outside the Lab*, hosted by ASU's Consortium for Science, Policy & Outcomes (CSPO), an immersive training experience which explores the relationships among science, policy, and societal outcomes in Washington, D.C.

Note: The travel budget was estimated in accordance with the University's travel policy (see http://www.asu.edu/aad/manuals/fin/index.html#500) based on current air fares, current ASU authorized per diem rates (http://www.gao.az.gov/publications/SAAM/Supp_I_trvrates-012308.pdf), airport shuttle services, and, if applicable, conference registration fees and/or car rental.

G. Other Direct Costs

Surgical and General Materials and Supplies: Funds are requested for surgery related expenses and other materials and supplies necessary for the successful completion of the proposed work.

	Year 1	Year 2	Year 3	Year 4	Year 5
Rhesus macaque monkeys 4@$6,000 ea	$24,000	$0	$0	$0	$0
Animal maintenance	$23,952	$23,952	$0	$18,952	$15,047
Computers 2@$3,000	$6,000	$0	$0	$0	$0
Materials	$21,444	$14,198	$0	$6,290	$0
Equipment maintenance	$5,000	$5,000	$0	$5,000	$0
Total	**$80,396**	**$43,150**	**$0**	**$30,242**	**$15,047**

These expenses include animal purchases (2 Rhesus macaque monkeys in year 1; $24,000 total including transportation costs), computers (2 in year 1; $6000 total), animal per diems (years 1-2,4-5; $81,903 total), microelectrode arrays (3 in years 1 and 2; $24,000 total), supplies for implantation and maintenance of the arrays, fixation pedestals, and associated hardware ($10,000 years 1-5), and materials and supplies for maintenance of primate chairs and testing apparatus ($7,932 in years 1-5).

Publication costs: Funds are requested ($6,250 total) to support publications in high impact factor journals such as *Nature Neuroscience, Neuron, Journal of Neuroscience and Journal of Neurophysiology*.

Tuition Remission: The tuition charge for the graduate students is $15,584 ($46,752 for 3 students) for YR-1 and an 8% escalation rate on tuition for years beyond FY-16. Tuition for the graduate student is included as a mandatory benefit and is charged in proportion to the amount of effort the graduate student will work on the project. Tuition charges are exempt from Facilities & Administrative costs.

Type of Application	Period of Support	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021 and beyond
New and Renewal*	AY	$14,632	$15,803	$17,067	$18,432	$19,907	Escalate tuition at 8% per year
New and Renewal*	Summer	$ 952	$ 1,028	$ 1,110	$ 1,199	$ 1,295	
	Total	$15,584	$16,831	$18,177	$19,631	$21,202	

H. Facilities and Administration (F&A) Costs

Indirect costs were calculated on Modified Total Direct Costs (MTDC) using F&A rates approved by the U.S. Department of Health and Human Services. The current rate for projects like the one proposed here, organized research, is 54.5% for FY17. The most current rate agreement is dated May 13, 2016. Items excluded from F&A calculation include: capital equipment, subcontracts over the first $25,000, a portion of the student tuition remission, participant support, rental/maintenance of off-campus space, and patient care fees.

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION **New York University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Bijan Pesaran**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Bijan Pesaran - Associate Professor**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					

D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)

Computer Server **$ 5,000**

	Funds Requested By proposer	Funds granted by NSF (if different)
TOTAL EQUIPMENT	**5,000**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)	**2,503**	
2. INTERNATIONAL	**0**	

F. PARTICIPANT SUPPORT COSTS

1. STIPENDS $ **0**
2. TRAVEL **0**
3. SUBSISTENCE **0**
4. OTHER **0**

TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS	**0**	
G. OTHER DIRECT COSTS		
1. MATERIALS AND SUPPLIES	**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION	**0**	
3. CONSULTANT SERVICES	**0**	
4. COMPUTER SERVICES	**0**	
5. SUBAWARDS	**0**	
6. OTHER	**0**	
TOTAL OTHER DIRECT COSTS	**0**	
H. TOTAL DIRECT COSTS (A THROUGH G)	(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct Costs (Rate: 58.5000, Base** (b)(4), (b)(6) [redacted]		
TOTAL INDIRECT COSTS (F&A)		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)	**126,893**	
K. SMALL BUSINESS FEE	**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	**126,893**	

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME **Bijan Pesaran**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Nancy daneau**	Date Checked	Date Of Rate Sheet	Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

Revised Proposal Budget Revision # 1 for 1557886 Submitted On Jul 15 2016 4:10PM Electronic Signature

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION **New York University**	PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Bijan Pesaran**	AWARD NO.	

FOR NSF USE ONLY

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Bijan Pesaran - Associate Professor**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**1,576**	
2. INTERNATIONAL				**0**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**0**	
TOTAL OTHER DIRECT COSTS				**0**	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct Costs (Rate: 58.5000, Base:** (b)(4), (b)(6) [redacted] TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**35,350**	
K. SMALL BUSINESS FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**35,350**	
M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $					

PI/PD NAME **Bijan Pesaran**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Nancy daneau**	Date Checked	Date Of Rate Sheet	Initials - ORG

2 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 4

ORGANIZATION **New York University**			FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Bijan Pesaran**			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Bijan Pesaran - Associate Professor**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**2,451**	
2. INTERNATIONAL				**0**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**0**	
TOTAL OTHER DIRECT COSTS				**0**	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct Costs (Rate: 58.5000, Base** (b)(4), (b)(6) [redacted] TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**55,000**	
K. SMALL BUSINESS FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**55,000**	
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME **Bijan Pesaran**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Nancy daneau**	Date Checked	Date Of Rate Sheet	Initials - ORG

4 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 5

ORGANIZATION **New York University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Bijan Pesaran**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Bijan Pesaran - Associate Professor**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEED					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**1,115**	
2. INTERNATIONAL				**0**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**0**	
TOTAL OTHER DIRECT COSTS				**0**	
H. TOTAL DIRECT COSTS (A THROUGH G)				(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct Costs (Rate: 58.5000, Base:** (b)(4), (b)(6) [redacted] TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**25,000**	
K. SMALL BUSINESS FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**25,000**	
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME **Bijan Pesaran**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Nancy daneau**	Date Checked	Date Of Rate Sheet	Initials - ORG

5 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION **New York University**	**FOR NSF USE ONLY** PROPOSAL NO.	DURATION (months) Proposed	 Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Bijan Pesaran**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Bijan Pesaran - Associate Professor**	(b)(4), (b)(6) [redacted]				
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE					
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					

D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) **$ 5,000**		
TOTAL EQUIPMENT	**5,000**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)	**7,645**	
2. INTERNATIONAL	**0**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**		
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS	**0**	
G. OTHER DIRECT COSTS		
1. MATERIALS AND SUPPLIES	**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION	**0**	
3. CONSULTANT SERVICES	**0**	
4. COMPUTER SERVICES	**0**	
5. SUBAWARDS	**0**	
6. OTHER	**0**	
TOTAL OTHER DIRECT COSTS	**0**	
H. TOTAL DIRECT COSTS (A THROUGH G)	(b)(4), (b)(6) [redacted]	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)		
TOTAL INDIRECT COSTS (F&A)		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)	**242,243**	
K. SMALL BUSINESS FEE	**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	**242,243**	
M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $		

PI/PD NAME **Bijan Pesaran**	**FOR NSF USE ONLY**		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Nancy daneau**	Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

Budget Justification

Personnel

Name: Bijan Pesaran Role on Project: Co-Investigator
Person Months: [redacted]
Functions: Responsible for the oversight of the Pesaran lab component of the project. He will coordinate with the co-PI Buneo and postdoctoral fellow to design experiments, analyze the data and publish the work. Finally, he will be responsible for interfacing with the Arizona State University, the lead organization, on all budgetary and other administrative issues. Note that the budget requests additional months in year 1 in order to carry-forward support to years 2 and 3.

Fringe Benefits

The fringe benefit rate for the PI and staff is 29% as per NYU's agreement with DHHS dated December 14, 2015. All future year faculty and research staff salaries are calculated assuming a [redacted] annual inflation rate.

Equipment

Computer server: A data storage server and computer will be purchased in year 1 to support the data storage and computation for the project.

Other Direct Costs:

1. **Travel**
   a. **Domestic Travel** Funds are requested for the co-I to visit the lead organization, Arizona State University each year.

Facilities and Administration

In accordance with the DHHS agreement dated 12/14/15, indirect costs are calculated on a modified total direct cost (MTDC) base. Effective 9/1/15 and onward, indirect costs are 58.5% of MTDC, excluding tuition remission, capital equipment $3,000 or greater, and subcontracts in excess of $25,000.

Budget Impact Statement

Overall the budget for the entire proposal was decreased by 35%. The following changes to the subcontract to NYU were necessary to accommodate the new budget:
1) Equipment support reduced by 50%
2) Funds for travel reduced by 80%
Despite these changes we are confident that all of the experimental work can be realistically completed within five years and without significantly impacting the overall aims of the project.

From: ethiels@nsf.gov
Reply-To: ethiels@nsf.gov
To: bijan@nyu.edu; osp.agency@nyu edu; bijan@nyu edu
CC: ethiels@nsf.gov; rwrhine@nsf.gov
Subject: NSF Approval of Continuing Grant Increment - Award ID - 1557886
Status: Sent on Thu 09/03/2020 03:19 PM

Notification of NSF Approval of Additional Funding Support

Award No 1557886
Amendment No 003
Division Identifier: IOS
Release Date: 09/03/2020
Released By: Edda Thiels
Amount: $25,000
Award End Date: 08/31/2021

As authorized by the original award, the National Science Foundation hereby releases $25,000 for additional support of the award referenced above The award, with this amendment, now totals $242,243 and will end on 08/31/2021

The attached budget indicates the amounts, by categories, on which NSF has based its continued support

This award is subject to the terms and conditions referenced in the original award notice The most current version of the terms and conditions can be accessed at: https://www nsf gov/awards/managing/award_conditions jsp?org=NSF

This award is subject to the Uniform Administrative Requirements, Cost Principles and Audit Requirements for Federal Awards (Uniform Guidance) NSF's implementation of the Uniform Guidance is contained in the Grant Conditions referenced in this award

Any technical or programmatic questions regarding this notification should be addressed to the cognizant NSF Program Officer: Edda Thiels , ethiels@nsf gov, (703)292-8167

Any award specific questions of an administrative or financial nature should be addressed to the grants official at http://www nsf gov/bfa/dga/docs/liaison pdf The cognizant grants official can be identified by associating the three-letter division identifier referenced above with the grants official for that division on the liaison website

NATIONAL SCIENCE FOUNDATION

PROPOSAL BUDGET

ORGANIZATION	FOR NSF USE ONLY		
New York University	PROPOSAL NO.	DURATION (months)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Pesaran, Bijan**	AWARD NO. **1557886**		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each seperately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUM	Funds Requested by proposer	Funds granted by NSF (if different)
1.				$	$
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)					
7. (**1**) TOTAL SENIOR PERSONNEL (1-6)	(b)(4), (b)(6) [redacted]				
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENIFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENIFITS (A + B + C)					

		Funds Requested by proposer	Funds granted by NSF (if different)
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5000.)			
1	$		
2	$		
3	$		
Others: (see budget comment page ...)	$		
TOTAL EQUIPMENT			0
E. TRAVEL	1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)		1,115
	2. INTERNATIONAL		0
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS $			
2. TRAVEL			
3. SUBSISTENCE			
4. OTHER			
(**0**) TOTAL PARTICIPANT COSTS			0
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES			0
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION			0
3. CONSULTANT SERVICES			0
5. COMPUTER SERVICES			0
5. SUBAWARDS			0
6. OTHER			0
TOTAL OTHER DIRECT COSTS			0
H. TOTAL DIRECT COSTS (A THROUGH G)			(b)(4), (b)(6) [redacted]
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)			
TOTAL INDIRECT COSTS (F&A)			
J. TOTAL DIRECT AND INDIRECT COSTS (A THROUGH G)			25,000
K. FEE			
K1 RESIDUAL FUNDS			0
K2 FEE			0
L. AMOUNT OF THIS REQUEST(J) OR (J - K1 + K2)		$	$ 25,000

M. COST SHARING PROPOSED LEVEL $ **0**		AGREED LEVEL IF DIFFERENT $		
PI/PD TYPED NAME & SIGNATURE*	DATE	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - ORG

NSF Form 1030 (10/99) Supersedes all previous editions ***SIGNATURES REQUIRED ONLY FOR REVISED BUDGET**

From: ethiels@nsf.gov
Reply-To: ethiels@nsf.gov
To: christopher buneo@asu.edu; asu.awards@asu edu; christopher.buneo@asu.edu
CC: ethiels@nsf.gov; rwrhine@nsf.gov
Subject: NSF Approval of Continuing Grant Increment - Award ID - 1558151
Status: Sent on Thu 09/03/2020 03:25 PM

Notification of NSF Approval of Additional Funding Support

Award No 1558151
Amendment No 003
Division Identifier: IOS
Release Date: 09/03/2020
Released By: Edda Thiels
Amount: $100,000
Award End Date: 08/31/2021

As authorized by the original award, the National Science Foundation hereby releases $100,000 for additional support of the award referenced above The award, with this amendment, now totals $1,271,492 and will end on 08/31/2021

The attached budget indicates the amounts, by categories, on which NSF has based its continued support

This award is subject to the terms and conditions referenced in the original award notice The most current version of the terms and conditions can be accessed at: https://www nsf gov/awards/managing/award conditions jsp?org=NSF

This award is subject to the Uniform Administrative Requirements, Cost Principles and Audit Requirements for Federal Awards (Uniform Guidance) NSF's implementation of the Uniform Guidance is contained in the Grant Conditions referenced in this award

Any technical or programmatic questions regarding this notification should be addressed to the cognizant NSF Program Officer: Edda Thiels , ethiels@nsf gov, (703)292-8167

Any award specific questions of an administrative or financial nature should be addressed to the grants official at http://www nsf gov/bfa/dga/docs/liaison pdf The cognizant grants official can be identified by associating the three-letter division identifier referenced above with the grants official for that division on the liaison website

NATIONAL SCIENCE FOUNDATION

PROPOSAL BUDGET

	FOR NSF USE ONLY		
ORGANIZATION **Arizona State University**	PROPOSAL NO.	DURATION (months)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Buneo, Christopher A.**	AWARD NO. **1558151**		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each seperately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUM	Funds Requested by proposer	Funds granted by NSF (if different)
1.				$	$
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)					
7. (**1**) TOTAL SENIOR PERSONNEL (1-6)	(b) (4), (b) (6) [redacted]				
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS					
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**0**) GRADUATE STUDENTS					
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENIFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENIFITS (A + B + C)					
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5000.) **1** $ **2** $ **3** $ **Others: (see budget comment page ...)** $					
TOTAL EQUIPMENT					**0**
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					**0**
2. INTERNATIONAL					**0**
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
(**0**) TOTAL PARTICIPANT COSTS					**0**
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					**15,047**
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					**0**
3. CONSULTANT SERVICES					**0**
5. COMPUTER SERVICES					**0**
5. SUBAWARDS					**0**
6. OTHER					**0**
TOTAL OTHER DIRECT COSTS					**15,047**
H. TOTAL DIRECT COSTS (A THROUGH G)					(b)(4) [redacted]
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)					
J. TOTAL DIRECT AND INDIRECT COSTS (A THROUGH G)					**100,000**
K. FEE					
K1 RESIDUAL FUNDS					**0**
K2 FEE					**0**
L. AMOUNT OF THIS REQUEST(J) OR (J - K1 + K2)				$	$ **100,000**

M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $			
PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - ORG

NSF Form 1030 (10/99) Supersedes all previous editions

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET

NATIONAL SCIENCE FOUNDATION

Award Notice

Award Number (FAIN): 1557886

Managing Division Abbreviation:
IOS

Amendment Number: 004

AWARDEE INFORMATION

Award Recipient: New York University
Awardee Address: 70 Washington Square S New York, NY 100121019
Official Awardee Email Address: osp.agency@nyu.edu
Unique Entity Identifier (DUNS ID): 041968306

AMENDMENT INFORMATION

Amendment Type: Other Admin No Fund Actions
Amendment Date: 10/06/2020
Amendment Number: 004
Proposal Number: Not Applicable
Amendment Description:

This award incorporates the following terms and conditions that implement Sections §§ 200.216 and 200.340 of the revised 2 CFR § 200 which was published in the Federal Register on August 13, 2020. The revised 2 CFR § 200 is effective on November 12, 2020, except for sections § 200.216 and § 200.340, which are effective on August 13, 2020:

1. Section 889 of the John S. McCain National Defense Authorization Act for Fiscal Year 2019

Section 889 of the John S. McCain National Defense Authorization Act for Fiscal Year 2019, of the National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2019 (Public Law 115-232), prohibits the use of loan or grant funds to procure or obtain, extend, or renew a contract to procure or obtain, or enter into a contract (or extend or renew a contract) to procure or obtain the equipment, services, or systems prohibited systems as identified in section 889 of the NDAA for FY 2019.

In accordance with the newly revised 2 CFR § 200.216 and § 200.471, a recipient and subrecipient are prohibited from entering into contracts (or extending or renewing contracts) with entities that use covered telecommunications equipment or services. This prohibition shall apply even if the contract is not intended to procure or obtain any equipment, system, or service that uses covered telecommunications equipment or services.

For the purposes of this article,

1. COVERED TELECOMMUNICATIONS EQUIPMENT OR SERVICES means any of the following:

- Telecommunications equipment produced by Huawei Technologies Company or ZTE Corporation (or any subsidiary or affiliate of such entities);
- For the purpose of public safety, security of government facilities, physical security surveillance of critical infrastructure, and other national security purposes, video surveillance and telecommunications equipment produced by Hytera Communications Corporation, Hangzhou Hikvision Digital Technology Company, or Dahua Technology Company (or any subsidiary or affiliate of such entities);
- Telecommunications or video surveillance services provided by such entities or using such equipment; or
- Telecommunications or video surveillance equipment or services produced or provided by an entity that the Secretary of Defense, in consultation with the Director of the National Intelligence or the Director of the Federal Bureau of Investigation, reasonably believes to be an entity owned or controlled by, or otherwise connected to, the government of a covered foreign country.

2. COVERED FOREIGN COUNTRY means the People's Republic of China.

2. Implementation of the newly revised section 2 CFR § 200.340

1. By NSF, if the awardee fails to comply with the terms and conditions of a Federal award;
2. By NSF, to the greatest extent authorized by law, if an award no longer effectuates the program goals or agency priorities;
3. By NSF, with the consent of the awardee, in which case the two parties must agree upon the termination conditions, including the effective date and, in the case of partial termination, the portion to be terminated;
4. By the awardee upon sending to NSF written notification setting forth the reasons for such termination, the effective date, and, in the case of partial termination, the portion to be terminated. However, if NSF determines in the case of partial termination that the reduced or modified portion of the NSF award will not accomplish the purposes for which the NSF award was made, NSF may terminate the Federal award in its entirety;
5. By NSF, pursuant to termination provisions included in the NSF award; or
6. By NSF, when ordered by the Deputy Director under NSF's Regulation on Research Misconduct [45 CFR Part 689].

PROJECT PERSONNEL

Principal Investigator: Bijan Pesaran

Email: bijan@nyu.edu

Institution: New York University

NSF CONTACT INFORMATION

Managing Grants Official (Primary Contact)	Awarding Official	Managing Program Officer
Name: Denise L Hundley	**Name:** Pamela A. Hawkins	**Name:** Edda Thiels
Email: dhundley@nsf.gov	**Email:** pahawkin@nsf.gov	**Email:** ethiels@nsf.gov

NATIONAL SCIENCE FOUNDATION

Award Notice

Award Number (FAIN): 1558151

Managing Division Abbreviation: IOS

Amendment Number: 004

AWARDEE INFORMATION

Award Recipient: Arizona Board of Regents Arizona State University
Awardee Address: ORSPA 660 South Mill Avenue, Suite 310 Tempe, AZ 852816011
Official Awardee Email Address: asu.awards@asu.edu
Unique Entity Identifier (DUNS ID): 943360412

AMENDMENT INFORMATION

Amendment Type: Other Admin No Fund Actions
Amendment Date: 10/06/2020
Amendment Number: 004
Proposal Number: Not Applicable
Amendment Description:

This award incorporates the following terms and conditions that implement Sections §§ 200.216 and 200.340 of the revised 2 CFR § 200 which was published in the Federal Register on August 13, 2020. The revised 2 CFR § 200 is effective on November 12, 2020, except for sections § 200.216 and § 200.340, which are effective on August 13, 2020:

1. Section 889 of the John S. McCain National Defense Authorization Act for Fiscal Year 2019

Section 889 of the John S. McCain National Defense Authorization Act for Fiscal Year 2019, of the National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2019 (Public Law 115-232), prohibits the use of loan or grant funds to procure or obtain, extend, or renew a contract to procure or obtain, or enter into a contract (or extend or renew a contract) to procure or obtain the equipment, services, or systems prohibited systems as identified in section 889 of the NDAA for FY 2019.

In accordance with the newly revised 2 CFR § 200.216 and § 200.471, a recipient and subrecipient are prohibited from entering into contracts (or extending or renewing contracts) with entities that use covered telecommunications equipment or services. This prohibition shall apply even if the contract is not intended to procure or obtain any equipment, system, or service that uses covered telecommunications equipment or services.

For the purposes of this article,

1. COVERED TELECOMMUNICATIONS EQUIPMENT OR SERVICES means any of the following:

- Telecommunications equipment produced by Huawei Technologies Company or ZTE Corporation (or any subsidiary or affiliate of such entities);
- For the purpose of public safety, security of government facilities, physical security surveillance of critical infrastructure, and other national security purposes, video surveillance and telecommunications equipment produced by Hytera Communications Corporation, Hangzhou Hikvision Digital Technology Company, or Dahua Technology Company (or any subsidiary or affiliate of such entities);
- Telecommunications or video surveillance services provided by such entities or using such equipment; or
- Telecommunications or video surveillance equipment or services produced or provided by an entity that the Secretary of Defense, in consultation with the Director of the National Intelligence or the Director of the Federal Bureau of Investigation, reasonably believes to be an entity owned or controlled by, or otherwise connected to, the government of a covered foreign country.

2. COVERED FOREIGN COUNTRY means the People's Republic of China.

2. Implementation of the newly revised section 2 CFR § 200.340

1. By NSF, if the awardee fails to comply with the terms and conditions of a Federal award;
2. By NSF, to the greatest extent authorized by law, if an award no longer effectuates the program goals or agency priorities;
3. By NSF, with the consent of the awardee, in which case the two parties must agree upon the termination conditions, including the effective date and, in the case of partial termination, the portion to be terminated;
4. By the awardee upon sending to NSF written notification setting forth the reasons for such termination, the effective date, and, in the case of partial termination, the portion to be terminated. However, if NSF determines in the case of partial termination that the reduced or modified portion of the NSF award will not accomplish the purposes for which the NSF award was made, NSF may terminate the Federal award in its entirety;
5. By NSF, pursuant to termination provisions included in the NSF award; or
6. By NSF, when ordered by the Deputy Director under NSF's Regulation on Research Misconduct [45 CFR Part 689].

PROJECT PERSONNEL

Principal Investigator: Christopher A Buneo

Email: christopher.buneo@asu.edu

Institution: Arizona State University

NSF CONTACT INFORMATION

Managing Grants Official	Awarding Official	Managing Program Officer
(Primary Contact) **Name:** Denise L Hundley **Email:** dhundley@nsf.gov	**Name:** Pamela A. Hawkins **Email:** pahawkin@nsf.gov	**Name:** Edda Thiels **Email:** ethiels@nsf.gov

NATIONAL SCIENCE FOUNDATION

Award Notice

Award Number (FAIN): 1557886

Managing Division Abbreviation:
IOS

Amendment Number: 005

AWARDEE INFORMATION

Award Recipient: New York University
Awardee Address: 70 Washington Square S New York, NY 100121019
Official Awardee Email Address: osp.agency@nyu.edu
Unique Entity Identifier (DUNS ID): 041968306

AMENDMENT INFORMATION

Amendment Type: Other Admin No Fund Actions
Amendment Date: 10/15/2020
Amendment Number: 005
Proposal Number: Not Applicable
Amendment Description:

This amendment replaces Term #1 implementing Section § 200.216 of the revised 2 CFR § 200 which was published in the Federal Register on August 13, 2020.

Except as modified by this amendment, the award conditions remain unchanged.

1. Section 889 of the John S. McCain National Defense Authorization Act for Fiscal Year 2019

Section 889 of the National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2019 (Public Law 115-232) prohibits the head of an executive agency from obligating or expending loan or grant funds to procure or obtain, extend, or renew a contract to procure or obtain, or enter into a contract (or extend or renew a contract) to procure or obtain the equipment, services, or systems prohibited systems as identified in section 889 of the NDAA for FY 2019.

(a) In accordance with 2 CFR 200.216 and 200.471, all awards that are issued on or after August 13, 2020, recipients and subrecipients are prohibited from obligating or expending loan or grant funds to:

(1) Procure or obtain;

(2) Extend or renew a contract to procure or obtain; or

(3) Enter into a contract (or extend or renew a contract) to procure or obtain equipment, services, or systems that uses covered telecommunications equipment or services as a substantial or essential component of any system, or as critical technology as part of any system. As described in Public Law 115-232, section 889, covered telecommunications equipment is telecommunications equipment produced by Huawei Technologies Company or ZTE Corporation (or any subsidiary or affiliate of such entities).

(i) For the purpose of public safety, security of government facilities, physical security surveillance of critical infrastructure, and other national security purposes, video surveillance and telecommunications equipment produced by Hytera Communications Corporation, Hangzhou Hikvision Digital Technology Company, or Dahua Technology Company (or any subsidiary or affiliate of such entities).

(ii) Telecommunications or video surveillance services provided by such entities or using such equipment.

(iii) Telecommunications or video surveillance equipment or services produced or provided by an entity that the Secretary of Defense, in consultation with the Director of the National Intelligence or the Director of the Federal Bureau of Investigation, reasonably believes to be an entity owned or controlled by, or otherwise connected to, the government of a covered foreign country.

(b) In implementing the prohibition under Public Law 115-232, section 889, subsection (f), paragraph (1), heads of executive agencies administering loan, grant, or subsidy programs shall prioritize available funding and technical support to assist affected businesses, institutions and organizations as is reasonably necessary for those affected entities to transition from covered communications equipment and services, to procure replacement equipment and services, and to ensure that communications service to users and customers is sustained.

(c) See Public Law 115-232, section 889 for additional information.

COVERED FOREIGN COUNTRY means the People's Republic of China.

PROJECT PERSONNEL

Principal Investigator: Bijan Pesaran	**Email:** bijan@nyu.edu	**Institution:** New York University

NSF CONTACT INFORMATION

Managing Grants Official (Primary Contact) **Name:** Denise L Hundley	**Awarding Official** **Name:** Pamela A. Hawkins **Email:** pahawkin@nsf.gov	**Managing Program Officer** **Name:** Edda Thiels **Email:** ethiels@nsf.gov

Email: dhundley@nsf.gov

NATIONAL SCIENCE FOUNDATION

Award Notice

Award Number (FAIN): 1558151

Managing Division Abbreviation: IOS

Amendment Number: 005

AWARDEE INFORMATION

Award Recipient: Arizona Board of Regents Arizona State University
Awardee Address: ORSPA 660 South Mill Avenue, Suite 310 Tempe, AZ 852816011
Official Awardee Email Address: asu.awards@asu.edu
Unique Entity Identifier (DUNS ID): 943360412

AMENDMENT INFORMATION

Amendment Type: Other Admin No Fund Actions
Amendment Date: 10/15/2020
Amendment Number: 005
Proposal Number: Not Applicable
Amendment Description:

This amendment replaces Term #1 implementing Section § 200.216 of the revised 2 CFR § 200 which was published in the Federal Register on August 13, 2020.

Except as modified by this amendment, the award conditions remain unchanged.

1. Section 889 of the John S. McCain National Defense Authorization Act for Fiscal Year 2019

Section 889 of the National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2019 (Public Law 115-232) prohibits the head of an executive agency from obligating or expending loan or grant funds to procure or obtain, extend, or renew a contract to procure or obtain, or enter into a contract (or extend or renew a contract) to procure or obtain the equipment, services, or systems prohibited systems as identified in section 889 of the NDAA for FY 2019.

(a) In accordance with 2 CFR 200.216 and 200.471, all awards that are issued on or after August 13, 2020, recipients and subrecipients are prohibited from obligating or expending loan or grant funds to:

(1) Procure or obtain;

(2) Extend or renew a contract to procure or obtain; or

(3) Enter into a contract (or extend or renew a contract) to procure or obtain equipment, services, or systems that uses covered telecommunications equipment or services as a substantial or essential component of any system, or as critical technology as part of any system. As described in Public Law 115-232, section 889, covered telecommunications equipment is telecommunications equipment produced by Huawei Technologies Company or ZTE Corporation (or any subsidiary or affiliate of such entities).

(i) For the purpose of public safety, security of government facilities, physical security surveillance of critical infrastructure, and other national security purposes, video surveillance and telecommunications equipment produced by Hytera Communications Corporation, Hangzhou Hikvision Digital Technology Company, or Dahua Technology Company (or any subsidiary or affiliate of such entities).

(ii) Telecommunications or video surveillance services provided by such entities or using such equipment.

(iii) Telecommunications or video surveillance equipment or services produced or provided by an entity that the Secretary of Defense, in consultation with the Director of the National Intelligence or the Director of the Federal Bureau of Investigation, reasonably believes to be an entity owned or controlled by, or otherwise connected to, the government of a covered foreign country.

(b) In implementing the prohibition under Public Law 115-232, section 889, subsection (f), paragraph (1), heads of executive agencies administering loan, grant, or subsidy programs shall prioritize available funding and technical support to assist affected businesses, institutions and organizations as is reasonably necessary for those affected entities to transition from covered communications equipment and services, to procure replacement equipment and services, and to ensure that communications service to users and customers is sustained.

(c) See Public Law 115-232, section 889 for additional information.

COVERED FOREIGN COUNTRY means the People's Republic of China.

PROJECT PERSONNEL

Principal Investigator: Christopher A Buneo	**Email:** christopher.buneo@asu.edu	**Institution:** Arizona State University

NSF CONTACT INFORMATION

Managing Grants Official (Primary Contact) **Name:** Denise L Hundley	**Awarding Official** **Name:** Pamela A. Hawkins **Email:** pahawkin@nsf.gov	**Managing Program Officer** **Name:** Edda Thiels

Email: dhundley@nsf.gov **Email:** ethiels@nsf.gov

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Project Report Printer Friendly Version

Preview of Award 1558151 - Annual Project Report

Cover | Accomplishments | Products | Participants/Organizations | Impacts | Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	**4900**
Federal Grant or Other Identifying Number Assigned by Agency:	**1558151**
Project Title:	**Collaborative Research: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
PD/PI Name:	**Christopher A Buneo, Principal Investigator**
Recipient Organization:	**Arizona State University**
Project/Grant Period:	**09/15/2016 - 08/31/2021**
Reporting Period:	**09/15/2016 - 08/31/2017**
Submitting Official (if other than PD\PI):	**Christopher A Buneo Principal Investigator**
Submission Date:	**07/12/2017**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Christopher A Buneo**

Back to the top

Accomplishments

*** What are the major goals of the project?**

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations

interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Major activities included 1) Recruitment and training of lab personnel, 2) Training of animals, 3) Design and construction of the virtual reality training platform that will be used to accomplish all of the project's objectives.

Specific Objectives:

1) Characterize the effect of varying semantic information about limb structure on oscillatory and spiking activity *within* multimodal cortical areas during arm state estimation

Cross-modal sensory stimuli are integrated not only for the formation of body schema, which is used for action, but also for the formation of the **body image**, which contributes to our sense of limb ownership. The latter in particular appears to be strongly influenced by semantic knowledge about how the body is structured. Here we will characterize the effects of varying such semantic knowledge on spiking, LFP activity, and local (areal) neural coherence across multimodal networks of the frontal and parietal lobes which display varying visual/somatic feedback sensitivities (PMv, area 5, and 7b). Monkeys will make reaching movements while receiving semantic information of varying complexity in different experimental blocks, ranging from an abstract arm endpoint stimulus (a sphere) to a fully rendered monkey avatar arm. Analysis will focus on a short, 1 second static holding period preceding reaching movements to virtual targets. We predict that as semantic information becomes more complex (i.e. more arm-like), reach reaction times will decrease and recording sites associated with representing the **body image** will show progressively larger effects of integration. More specifically, we predict that neural population responses, indexed by LFP power in the gamma band (which has been implicated in body-ownership) will be progressively enhanced and will be coherent with the spikes emitted by the cells that show enhanced spiking. Conversely, we predict that sites associated with representing the **body schema** will show minimal or no effects of semantic complexity. Instead, presentation of any visual stimulus will generally result in suppressed LFP power in the beta band (implicated in sensorimotor state) at these sites, which will be coherent with the spikes of cells that are suppressed. Lastly, sites involved in representing both body image and body schema are predicted to show evidence of cross frequency (beta-gamma) coupling. Changes in spiking and the direction of this change (enhancement/suppression) should reflect the strength of coupling at these sites.

2) Elucidate changes in oscillatory and spiking activity *within* multimodal cortical areas as a function of changes in the relative reliability of visual and somatic position cues

Psychophysical studies have demonstrated that sensory signals are optimally (or near optimally) integrated during both perceptual and action tasks in that they are weighted according to their relative reliabilities. Cortical correlates of optimal integration have been identified at the single cell and population levels during perceptual tasks but not during motor tasks and network level correlates of multimodal integration are poorly understood in general. As a result, in SA2 we will quantify changes in spiking, LFP activity, and local neural coherence in frontal and parietal areas as a function of the reliability of visual state (position) information. As in SA1 monkeys will make reaching movements to virtual targets and analysis will focus on the static holding period preceding the reach. Reliability of the visual information will be varied on a trial by trial basis by providing either a clear visual stimulus, one of two levels of a blurred visual stimulus, or no visual stimulus. We predict that as visual state information becomes more reliable, variability in limb positions will decrease and recording sites associated with representing the body schema will show progressively larger effects of integration. Specifically, we predict that LFP power in the beta band will be progressively suppressed and will be coherent with the spikes of cells that show suppressed spiking. Conversely, we predict that sites associated with representing the body image will show minimal or no effects of visual reliability. Instead, presentation of visual stimuli that recruited the body image in SA1 will generally result in enhanced LFP power in the gamma band , which will be coherent with the spikes of cells that are enhanced. Lastly, sites involved in representing both body image and body schema should again show evidence of cross frequency (beta-gamma) coupling and changes in spiking that reflect the strength of coupling.

3) Characterize changes in functional connectivity *among* multimodal cortical areas as a function of changes in semantic information and sensory reliability.

For this aim, no new experiments will be conducted. Instead this aim will focus on quantifying the degree of functional connectivity among sites in multimodal parietal and frontal areas. That is, we predict that sites involved in body schema and/or body image will show strong evidence of functional connectivity, assessed via inter-areal (long-range) neural coherence. More specifically, sites involved in body image will change show progressively stronger correlations as semantic information increases and sites involved in representing the body schema will show progressively stronger correlations as visual state information increases. However we hypothesize that changes in functional connectivity will be stronger between sites with similar visual-somatic sensitivities. That is, increasing the reliability or semantic information of visual signals should be associated with stronger changes in correlations between sites in strongly-moderately visual areas (PMv and 7b) than between areas that are strongly-moderately somatosensory (area 5 and 7b).

Significant Results:	Nothing to report – as we are still currently modifying the laboratory to accommodate the project objective, as well as training staff and animals, there are no results to report at this time.
Key outcomes or Other achievements:	Regarding the major activities 1-3 discussed above: 1) We have recruited one PhD student, a technician and an undergraduate student to work on the project. Recruitment of the undergraduate student will provide needed technical assistance while enhancing the Broader Impacts of the work, as described in the original proposal. We have also discussed the postdoctoral position with two candidates thus far but have not yet made a hire for this position. 2) One animal is currently being acclimated to the testing room environment and to wearing the garment that will be used to mount reflective motion tracking markers. 3) We have purchased and installed a new motion tracking system and associated software for rendering visual information about the limb in real-time.

*** What opportunities for training and professional development has the project provided?**

During the last project period the project has enhanced the mentoring of 2 PhD students (1 female), 1 lab technician, 1 lab manager/animal technician, and 1 undergraduate student.

In addition, the PI attended the 2017 Neural Control of Movement meeting, as well as a satellite to this meeting that was entirely devoted to proprioception.

*** How have the results been disseminated to communities of interest? If so, please provide details.**

Nothing to report – as we are still currently modifying the laboratory to accommodate the project objective, as well as training staff and animals, there are no results to disseminate at this time.

*** What do you plan to do during the next reporting period to accomplish the goals?**

During the next reporting period we will do the following:

1) Complete modifications to the lab, including the installation of a new neural recording system

2) Continue with training of essential personnel and complete recruitment of a postdoctoral fellow

3) Complete training of one animal on the behavioral tasks, begin training of a second animal

4) Implant one animal with three recording arrays

5) Begin neural recordings in one animal

6) Provide opportunties for more undergraduates to get involved in the project in order to enhance the Broader Impacts of the work.

7) To further enhance the Broader Impacts, encourage the PhD student and undergraduate students to participate in colloquia at organized by local and national organizations engaged in the ethical, societal, and policy implications of neuroscience research.

Supporting Files

	Filename	Description	Uploaded By	Uploaded On
(Download)	Lab_modifications.pdf	Modifications to laboratory	Christopher Buneo	06/22/2017

Back to the top

Products

Books

Nothing to report.

Book Chapters

Nothing to report.

Inventions

Nothing to report.

Journals or Juried Conference Papers

Nothing to report.

Licenses

Nothing to report.

Other Conference Presentations / Papers

Nothing to report.

Other Products

Nothing to report.

Other Publications

Nothing to report.

Patent Applications

Nothing to report.

Technologies or Techniques

Nothing to report.

Thesis/Dissertations

Nothing to report.

Websites or Other Internet Sites

Nothing to report.

Back to the top

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Buneo, Christopher	PD/PI	(b)(4), (b)(6) [redacted]
VanGilder, Paul	Graduate Student (research assistant)	
(b) (6) [redacted]	Technician	
	Technician	
Phatarphruk, Preyaporn	Graduate Student (research assistant)	
(b) (6) [redacted]	Undergraduate Student	

Full details of individuals who have worked on the project:

Christopher A Buneo
Email: christopher.buneo@asu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: (b)(4), (b)(6) [redacted]

Contribution to the Project: Overall direction of the project, training of PhD student.
Funding Support: (b)(4), (b)(6) [redacted].
International Collaboration: No
International Travel: Yes, Ireland - 0 years, 0 months, 7 days

Paul VanGilder
Email: Paul.Vangilder@asu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of other graduate student, training of animal.
Funding Support: None.
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Most Senior Project Role: Technician
Nearest Person Month Worked: (b)(4), (b)(6) [redacted]
Contribution to the Project: Pro are to the animals; trained animals; trained graduate student, other technician and undergraduate student.
Funding Support: (b)(4), (b)(6) [redacted]
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Emai (b) (6) [redacted]
Most Senior Project Role: Technician
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of animals; providing assistance to vet tech/lab manager and graduate student.
Funding Support: None
International Collaboration: No
International Travel: No

Preyaporn Phatarphruk
Email: pphatara@asu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of animals, training of technician and undergraduate student, installation of motion tracking system and virtual reality training platform.
Funding Support: None.
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of animals; providing assistance to vet tech/lab manager and graduate student.
Funding Support: None.
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
New York University	Academic Institution	New York City

Full details of organizations that have been involved as partners:

New York University
Organization Type: Academic Institution
Organization Location: New York City
Partner's Contribution to the Project:
In-Kind Support

Collaborative Research
More Detail on Partner and Contribution: New York University is the home institution of B jan Pesaran, the co-PI/PD on the project.

What other collaborators or contacts have been involved?

Bijan Pesaran, New York University. As the co-PI/PD on the project, Dr. Pesaran will be submitting his own progress report.

Back to the top

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The proposed research has significant potential to impact our understanding of basic neural processes such as multisensory integration, state estimation, and sensorimotor control while also advancing the fundamental engineering knowledge necessary to create the next generation of brain-machine interfaces (BMIs). Next generation BMIs for replacing lost limb function are envisioned to support the integration of artificial somatosensory feedback (tactile/proprioceptive) with natural vision (Bensmaia and Miller, 2014). The feasibility of such systems has already been established using monkey models (Shokur et al., 2013; Dadarlat et al., 2015). Optimizing these systems however will depend critically on understanding how natural visual and somatosensory signals interact within and among multisensory brain areas and their associated neural networks. Here we will address this knowledge gap by quantifying changes in spiking, local field potential (LFP) activity and neural coherence that result from integration of natural visual and somatosensory signals generated during arm movements. This will be performed in frontal and parietal brain areas of the monkey that have been implicated in sensorimotor control of the arm. The joint analysis of spiking and local field potential activity measured at different sites in the brain offers a unique opportunity to examine functional interactions between neurons and ensembles of neurons across large-scale brain networks. Spike-field coherence is a measure of association using these signals that links different scales: ~10-50um for spiking activity and ~200-500um for local field potential activity. This provides a bridge to less invasive measures of neural activity such as electrocorticography on the surface of the brain and EEG non-invasively at the scalp.

Optimizing multisensory BMIs will also require understanding how perceptual and action-related brain representations evolve as subjects learn to use and ultimately embody these devices. Current state-of-the-art robotic devices are not yet capable of the real-time, high-dimensional, natural movements that are likely necessary for embodiment (Putrino et al., 2015). Even if such devices were currently available, other factors would likely make them impractical for patients to use without extensive training. Virtual devices however offer a safe and practical alternative to robotic ones, allowing a multitude of behaviors to be learned and trained (Bohil et al., 2011; Putrino et al., 2015). Precisely how realistic such environments need to be to enable embodiment is unclear; diverse virtual stimuli have been used in different studies, with no attempt to determine the optimal (or minimal) stimulus for enabling embodiment. The studies proposed here, which involve virtual reaching tasks that vary the degree of reliability and semantic information about limb structure, will provide critical insights in this regard. This information will in turn advance the development of BMIs and related assistive technologies designed to improve the quality of life of individuals with sensorimotor disabilities.

What is the impact on other disciplines?

Nothing to report.

What is the impact on the development of human resources?

To date this project has contributed to human resource development mostly by providing research opportunities for graduate students. In the last project period this has included opportunities for Preyaporn (Kris) Phataraphruk and Paul VanGilder.

Paul has mostly gained additional experience in basic and advanced data analysis techniques.
Kris has gained experience with the fundamental experimental techniques used in the lab including 1) animal training and handling, 2) basic surgical techniques, and most recently 3) motion capture and virtual reality techniques.

What is the impact on physical resources that form infrastructure?

The project has led to the rebuilding of one of the PI's laboratory at Arizona State University, which is associated with the acquistion and analysis of behavioral and neural data in non-human primates. These facilities are available for use by the PI and his collaborators at ASU.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

Nothing to report.
Back to the top

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

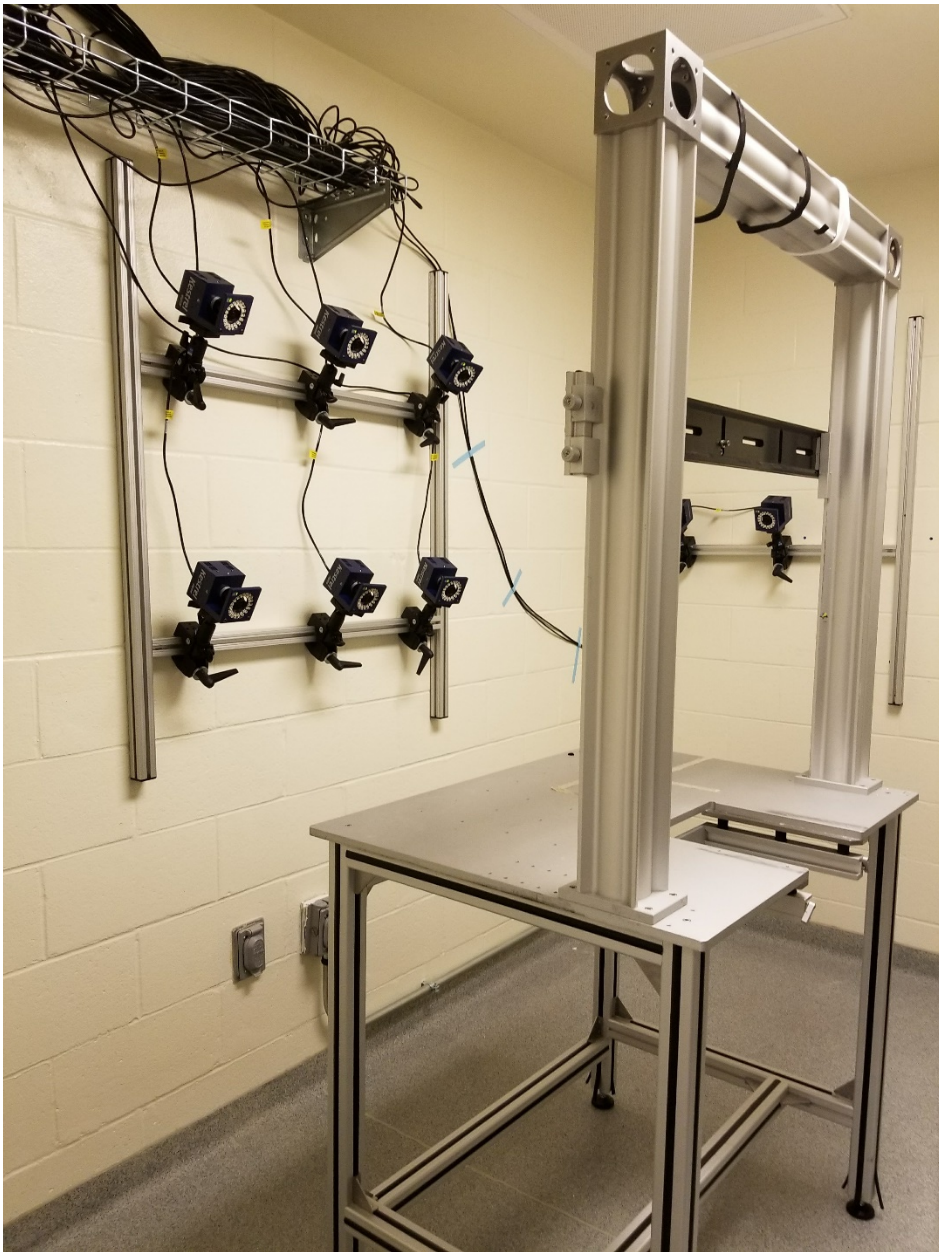
Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.
Back to the top

Newly installed Kestrel cameras from Motion Analysis Corp, part of the Kestrel Digital Real-time System



Project Report Printer Friendly Version

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Preview of Award 1557886 - Annual Project Report

Cover | Accomplishments | Products | Participants/Organizations | Impacts | Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	**4900**
Federal Grant or Other Identifying Number Assigned by Agency:	**1557886**
Project Title:	**Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
PD/PI Name:	**Bijan Pesaran, Principal Investigator**
Recipient Organization:	**New York University**
Project/Grant Period:	**09/15/2016 - 08/31/2021**
Reporting Period:	**09/15/2016 - 08/31/2017**
Submitting Official (if other than PD\PI):	**Bijan Pesaran** **Principal Investigator**
Submission Date:	**07/19/2017**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Bijan Pesaran**

Back to the top

Accomplishments

*** What are the major goals of the project?**

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the

relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Major activities included 1) Transfer of expertise in virtual reality, motion capture experiments to the Buneo Lab to purchase a suitable motion capture system for real-time animation of a virtual avatar, 2) Design and construction of the virtual reality training platform that will be used to accomplish all of the project's objectives.

Specific Objectives:

1) Characterize the effect of varying semantic information about limb structure on oscillatory and spiking activity *within* multimodal cortical areas during arm state estimation

Cross-modal sensory stimuli are integrated not only for the formation of body schema, which is used for action, but also for the formation of the **body image**, which contributes to our sense of limb ownership. The latter in particular appears to be strongly influenced by semantic knowledge about how the body is structured. Here we will characterize the effects of varying such semantic knowledge on spiking, LFP activity, and local (areal) neural coherence across multimodal networks of the frontal and parietal lobes which display varying visual/somatic feedback sensitivities (PMv, area 5, and 7b). Monkeys will make reaching movements while receiving semantic information of varying complexity in different experimental blocks, ranging from an abstract arm endpoint stimulus (a sphere) to a fully rendered monkey avatar arm. Analysis will focus on a short, 1 second static holding period preceding reaching movements to virtual targets. We predict that as semantic information becomes more complex (i.e. more arm-like), reach reaction times will decrease and recording sites associated with representing the **body image** will show progressively larger effects of integration. More specifically, we predict that neural population responses, indexed by LFP power in the gamma band (which has been implicated in body-ownership) will be progressively enhanced and will be coherent with the spikes emitted by the cells that show enhanced spiking. Conversely, we predict that sites associated with representing the **body schema** will show minimal or no effects of semantic complexity. Instead, presentation of any visual stimulus will generally result in suppressed LFP power in the beta band (implicated in sensorimotor state) at these sites, which will be coherent with the spikes of cells that are suppressed. Lastly, sites involved in representing both body image and body schema are predicted to show evidence of cross frequency (beta-gamma) coupling. Changes in spiking and the direction of this change (enhancement/suppression) should reflect the strength of coupling at these sites.

2) Elucidate changes in oscillatory and spiking activity *within* multimodal cortical areas as a function of changes in the relative reliability of visual and somatic position cues

Psychophysical studies have demonstrated that sensory signals are optimally (or near optimally) integrated during both perceptual and action tasks in that they are weighted according to their relative reliabilities. Cortical correlates of optimal integration have been identified at the single cell and population levels during perceptual tasks but not during motor tasks and network level correlates of multimodal integration are poorly understood in general. As a result, in SA2 we will quantify changes in spiking, LFP activity, and local neural coherence in frontal and parietal areas as a function of the reliability of visual state (position) information. As in SA1 monkeys will make reaching movements to virtual targets and analysis will focus on the static holding period preceding the reach. Reliability of the visual information will be varied on a trial by trial basis by providing either a clear visual stimulus, one of two levels of a blurred visual stimulus, or no visual stimulus. We predict that as visual state information becomes more reliable, variability in limb positions will decrease and recording sites associated with representing the body schema will show progressively larger effects of integration. Specifically, we predict that LFP power in the beta band will be progressively suppressed and will be coherent with the spikes of cells that show suppressed spiking. Conversely, we predict that sites associated with representing the body image will show minimal or no effects of visual reliability. Instead, presentation of visual stimuli that recruited the body image in SA1 will generally result in enhanced LFP power in the gamma band , which will be coherent with the spikes of cells that are enhanced. Lastly, sites involved in representing both body image and body schema should again show evidence of cross frequency (beta-gamma) coupling and changes in spiking that reflect the strength of coupling.

3) Characterize changes in functional connectivity *among* multimodal cortical areas as a function of changes in semantic information and sensory reliability.

For this aim, no new experiments will be conducted. Instead this aim will focus on quantifying the degree of functional connectivity among sites in multimodal parietal and frontal areas. That is, we predict that sites involved in body schema and/or body image will show strong evidence of functional connectivity, assessed via inter-areal (long-range) neural coherence. More specifically, sites involved in body image will change show progressively stronger correlations as semantic information increases and sites involved in representing the body schema will show progressively stronger correlations as visual state information increases. However we hypothesize that changes in functional connectivity will be stronger between sites with similar visual-somatic sensitivities. That is, increasing the reliability or semantic information of visual signals should be associated with stronger changes in correlations between sites in strongly-moderately visual areas (PMv and 7b) than between areas that are strongly-moderately somatosensory (area 5 and 7b).

Significant Results:	Nothing to report – as we are still assisting the Buneo lab to modify the laboratory to accommodate the project objective. There are no results to report at this time.
Key outcomes or Other achievements:	Regarding the major activities 1-2 discussed above: 1) We have shared technical documentation, software files that permit animation of an avatar of the non-human primate, and hardware designs to mount mirrors in order to generate three-dimensional percepts. 3) We have worked with the PI Buneo to purchase and install a new motion tracking system and associated software for rendering visual information about the limb in real-time. Co-I Pesaran conducted several teleconference calls to engage Motion Analysis in the needs for this project. These meetings were followed up with a site visit to the vendor to evaluate a demonstration system suitable for the needs of the project. This effort not only supports the reserach objectives of this project and will support new Broader Impacts for this project that we will develop in the next reporting interval, see below.

*** What opportunities for training and professional development has the project provided?**

During the last project period the project has enhanced the training of staff in the Buneo lab and in the Pesaran lab to establish the motion capture based virtual reality platform for use in the Buneo lab. Members of the Pesaran Lab learned to manipulate the avatar materials in state-of-the-art 3-D computer aided design and rendering software packages, specifically 3DS Max and Unity.

*** How have the results been disseminated to communities of interest? If so, please provide details.**

There are no results to disseminate at this time.

*** What do you plan to do during the next reporting period to accomplish the goals?**

During the next reporting period we will do the following:

1) Complete software installation of motion capture and virtual reality in the lab.

2) Develop tools to analyze spike-LFP activity to address the specific objectives described above.

3) We intend to expand our Broader Impacts by working closely with Motion Analysis Corp who has developed the motion capture technology we are using to expand the range of applications. The typical application of motion capture is to assess movement kinematics such as gait or reach-to-grasp by recording joint angles of during typical movement sets. Our project extends motion capture as it requires the use of a virtual reality interface in which the subjects own movements are rendered in real-time as an avatar. This rendering allows us to manipulate the sensory feedback we provide the subject assocated with movement and, for example, permits changes in embodiment that we will pursue. The connection of motioncapture with virtual reality depends on precise skeletal modeling is a growth area for the motion capture community. Work in this area is done from the perspective of animation as opposed to skeletal modeling and so the rendering does not leave the subject performing the control with the sense of realistic self-motion. During our visit to Motion Analysis Corp in Santa Rosa, we discussed developing this area with Motion Analysis. The Broader Impacts that will result from this effort will include tools for movement rehabilitation that can assist in recovery due to stroke and other neurological damage. They will also include new approaches for manipulating self-image that offer ways to treat chronic pain. In the next reporting period we will establish ways to enhance the adoption of motion capture by the relevant communities for these purposes.

Back to the top

Products

Books

Nothing to report.

Book Chapters

Nothing to report.

Inventions

Nothing to report.

Journals or Juried Conference Papers

Nothing to report.

Licenses

Nothing to report.

Other Conference Presentations / Papers

Nothing to report.

Other Products

Nothing to report.

Other Publications

Nothing to report.

Patent Applications

Nothing to report.

Technologies or Techniques

Nothing to report.

Thesis/Dissertations

Nothing to report.

Websites or Other Internet Sites

Nothing to report.

Back to the top

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Pesaran, Bijan	PD/PI	(b)(4), (b)(6) [redacted]
(b) (6) [redacted]	Undergraduate Student	[redacted]

Full details of individuals who have worked on the project:

Bijan Pesaran
Email: bijan@nyu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Co-
Funding Support (b)(4), (b)(6) [redacted]
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Development and use of motion capture labeling and rendering software.
Funding Support: None
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Christopher Buneo	Academic Institution	Phoenix, Arizona

Full details of organizations that have been involved as partners:

Christopher Buneo
Organization Type: Academic Institution
Organization Location: Phoenix, Arizona
Partner's Contribution to the Project:
Collaborative Research
More Detail on Partner and Contribution:

What other collaborators or contacts have been involved?

Nothing to report

[Back to the top](#)

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The proposed research has significant potential to impact our understanding of basic neural processes such as multisensory integration, state estimation, and sensorimotor control while also advancing the fundamental engineering knowledge necessary to create the next generation of brain-machine interfaces (BMIs). Next generation BMIs for replacing lost limb function are envisioned to support the integration of artificial somatosensory feedback (tactile/proprioceptive) with natural vision (Bensmaia and Miller, 2014). The feasibility of such systems has already been established using monkey models (Shokur et al., 2013; Dadarlat et al., 2015). Optimizing these systems however will depend critically on understanding how natural visual and somatosensory signals interact within and among multisensory brain areas and their associated neural networks. Here we will address this knowledge gap by quantifying changes in spiking, local field potential (LFP) activity and neural coherence that result from integration of natural visual and somatosensory signals generated during arm movements. This will be performed in frontal and parietal brain areas of the monkey that have been implicated in sensorimotor control of the arm. The joint analysis of spiking and local field potential activity measured at different sites in the brain offers a unique opportunity to examine functional interactions between neurons and ensembles of neurons across large-scale brain networks. Spike-field coherence is a measure of association using these signals that links different scales: ~10-50um for spiking activity and ~200-500um for local field potential activity. This provides a bridge to less invasive measures of neural activity such as electrocorticography on the surface of the brain and EEG non-invasively at the scalp.

Optimizing multisensory BMIs will also require understanding how perceptual and action-related brain representations evolve as subjects learn to use and ultimately embody these devices. Current state-of-the-art robotic devices are not yet capable of the real-time, high-dimensional, natural movements that are likely necessary for embodiment (Putrino et al., 2015). Even if such devices were currently available, other factors would likely make them impractical for patients to use without extensive training. Virtual devices however offer a safe and practical alternative to robotic ones, allowing a multitude of behaviors to be learned and trained (Bohil et al., 2011; Putrino et al., 2015). Precisely how realistic such environments need to be to enable embodiment is unclear; diverse virtual stimuli have been used in different studies, with no attempt to determine the optimal (or minimal) stimulus for enabling embodiment. The studies proposed here, which involve virtual reaching tasks that vary the degree of reliability and semantic information about limb structure, will provide critical insights in this regard. This information will in turn advance the development of BMIs and related assistive technologies designed to improve the quality of life of individuals with sensorimotor disabilities.

What is the impact on other disciplines?

Nothing to report.

What is the impact on the development of human resources?

To date this project has contributed to human resource development mostly by providing research and training opportunities for an undergraduate student in motion capture and virtual reality experiments.

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

Nothing to report.
Back to the top

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.
Back to the top

Project Report Printer Friendly Version

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Preview of Award 1558151 - Annual Project Report

Cover | Accomplishments | Products | Participants/Organizations | Impacts | Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	**4900**
Federal Grant or Other Identifying Number Assigned by Agency:	**1558151**
Project Title:	**Collaborative Research: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
PD/PI Name:	**Christopher A Buneo, Principal Investigator**
Recipient Organization:	**Arizona State University**
Project/Grant Period:	**09/15/2016 - 08/31/2021**
Reporting Period:	**09/01/2017 - 08/31/2018**
Submitting Official (if other than PD\PI):	**Christopher A Buneo Principal Investigator**
Submission Date:	**11/27/2018**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Christopher A Buneo**

Back to the top

Accomplishments

*** What are the major goals of the project?**

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations

interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities: Major activities included 1) Recruitment and training of lab personnel, 3) Design and construction of the virtual reality training platform that will be used to accomplish all of the project's objectives, 3) Training of animals.

Specific Objectives:

1) Characterize the effect of varying semantic information about limb structure on oscillatory and spiking activity *within* multimodal cortical areas during arm state estimation

Cross-modal sensory stimuli are integrated not only for the formation of body schema, which is used for action, but also for the formation of the **body image**, which contributes to our sense of limb ownership. The latter in particular appears to be strongly influenced by semantic knowledge about how the body is structured. Here we will characterize the effects of varying such semantic knowledge on spiking, LFP activity, and local (areal) neural coherence across multimodal networks of the frontal and parietal lobes which display varying visual/somatic feedback sensitivities (PMv, area 5, and 7b). Monkeys will make reaching movements while receiving semantic information of varying complexity in different experimental blocks, ranging from an abstract arm endpoint stimulus (a sphere) to a fully rendered monkey avatar arm. Analysis will focus on a short, 1 second static holding period preceding reaching movements to virtual targets. We predict that as semantic information becomes more complex (i.e. more arm-like), reach reaction times will decrease and recording sites associated with representing the **body image** will show progressively larger effects of integration. More specifically, we predict that neural population responses, indexed by LFP power in the gamma band (which has been implicated in body-ownership) will be progressively enhanced and will be coherent with the spikes emitted by the cells that show enhanced spiking. Conversely, we predict that sites associated with representing the **body schema** will show minimal or no effects of semantic complexity. Instead, presentation of any visual stimulus will generally result in suppressed LFP power in the beta band (implicated in sensorimotor state) at these sites, which will be coherent with the spikes of cells that are suppressed. Lastly, sites involved in representing both body image and body schema are predicted to show evidence of cross frequency (beta-gamma) coupling. Changes in spiking and the direction of this change (enhancement/suppression) should reflect the strength of coupling at these sites.

2) Elucidate changes in oscillatory and spiking activity *within* multimodal cortical areas as a function of changes in the relative reliability of visual and somatic position cues

Psychophysical studies have demonstrated that sensory signals are optimally (or near optimally) integrated during both perceptual and action tasks in that they are weighted according to their relative reliabilities. Cortical correlates of optimal integration have been identified at the single cell and population levels during perceptual tasks but not during motor tasks and network level correlates of multimodal integration are poorly understood in general. As a result, in SA2 we will quantify changes in spiking, LFP activity, and local neural coherence in frontal and parietal areas as a function of the reliability of visual state (position) information. As in SA1 monkeys will make reaching movements to virtual targets and analysis will focus on the static holding period preceding the reach. Reliability of the visual information will be varied on a trial by trial basis by providing either a clear visual stimulus, one of two levels of a blurred visual stimulus, or no visual stimulus. We predict that as visual state information becomes more reliable, variability in limb positions will decrease and recording sites associated with representing the body schema will show progressively larger effects of integration. Specifically, we predict that LFP power in the beta band will be progressively suppressed and will be coherent with the spikes of cells that show suppressed spiking. Conversely, we predict that sites associated with representing the body image will show minimal or no effects of visual reliability. Instead, presentation of visual stimuli that recruited the body image in SA1 will generally result in enhanced LFP power in the gamma band , which will be coherent with the spikes of cells that are enhanced. Lastly, sites involved in representing both body image and body schema should again show evidence of cross frequency (beta-gamma) coupling and changes in spiking that reflect the strength of coupling.

3) Characterize changes in functional connectivity *among* multimodal cortical areas as a function of changes in semantic information and sensory reliability.

For this aim, no new experiments will be conducted. Instead this aim will focus on quantifying the degree of functional connectivity among sites in multimodal parietal and frontal areas. That is, we predict that sites involved in body schema and/or body image will show strong evidence of functional connectivity, assessed via inter-areal (long-range) neural coherence. More specifically, sites involved in body image will change show progressively stronger correlations as semantic information increases and sites involved in representing the body schema will show progressively stronger correlations as visual state information increases. However we hypothesize that changes in functional connectivity will be stronger between sites with similar visual-somatic sensitivities. That is, increasing the reliability or semantic information of visual signals should be associated with stronger changes in correlations between sites in strongly-moderately visual areas (PMv and 7b) than between areas that are strongly-moderately somatosensory (area 5 and 7b).

Significant Results:

We have completed all major modifications to our VR-based behavioral control system, allowing us to train animals on the behavioral tasks described in the proposal. The main software components of this system are Cortex (the software interface for the Motion Analysis motion capture system), LabVIEW, and Unity 3D. Cortex records the marker positions and uses Calcium Solver, a built in skeletal engine, to generate a segment model which is streamed to Unity to animate a custom avatar (created in Maya). Labview controls the sequence of events on a given trial, including sending the coordinates of reach targets to Unity for rendering. Unity, in addition to rendering the avatar, targets, and other components of the VR environment, sends the current position of the endpoint of the arm to Labview to allow for checking of arm position against target position, allowing the task to proceed and for behavioral reinforcement to occur.

Key outcomes or Other achievements:

Regarding the major activities discussed above:

1) One PhD student, a Master's student, a technician, a lab manager/vet tech and 2 undergraduates currently work on the project. We have discussed the postdoctoral position with several candidates thus far and another candidate will be interviewed the last week in November. If a suitable candidate cannot be found we may explore the option of hiring a second PhD student instead.

2) We have successfully incorporated a new motion capture system (Motion Analysis Corp.) and a new VR engine (Unity 3D) into our behavioral paradigm which allow us to render visual information about the entire limb in real-time.

3) One animal is currently being trained on a preliminary version of the VR task that we will use during neural recordings. We are currently discussing transfer of a second animal from another investigator’s protocol. This animal is already trained on similar types of behavioral tasks which should accelerate the training process.

*** What opportunities for training and professional development has the project provided?**

During the last project period the project has enhanced the mentoring of 1 PhD student (1 female), 1 Master's student, 1 lab technician, 2 lab manager/animal technician, and 1 undergraduate students.

*** How have the results been disseminated to communities of interest? If so, please provide details.**

Nothing to report.

*** What do you plan to do during the next reporting period to accomplish the goals?**

During the next reporting period we plan to do the following:

1) Complete installation of a new neural recording system

2) Complete training of the first animal on tasks related to Aim 1.

2) Implant first animal with microelectrode arrays and begin addressing the specific objectives of Aim 1 in this animal.

3) Begin training of second animal.

4) Recruit postdoctoral fellow or a 2nd PhD student to work on the project.

5) To enhance Broader impacts, recruit additional undergraduates to be involved in the project and encourage them and other students to participate in colloquia addressing the ethical, societal and policy implications of neuroscience research.

Supporting Files

	Filename	Description	Uploaded By	Uploaded On
(Download)	Supporting_Documentation.pdf	Supporting images showing progress made on developing VR-based behavioral control system.	Christopher Buneo	11/26/2018

Back to the top

Products

Books

Nothing to report.

Book Chapters

Nothing to report.

Inventions

Nothing to report.

Journals or Juried Conference Papers

Nothing to report.

Licenses

Nothing to report.

Other Conference Presentations / Papers

Nothing to report.

Other Products

Nothing to report.

Other Publications

Nothing to report.

Patent Applications

Nothing to report.

Technologies or Techniques

Nothing to report.

Thesis/Dissertations

Nothing to report.

Websites or Other Internet Sites

Nothing to report.

[Back to the top]

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Buneo, Christopher	PD/PI	(b)(4), (b)(6) [redacted]
(b) (6) [redacted]	Technician	[redacted]
[redacted]	Technician	[redacted]

(b) (6) [redacted]	Technician	(b)(4), (b)(6) [redacted]	
Phatarphruk, Preyaporn	Graduate Student (research assistant)		
(b) (6) [redacted]	Graduate Student (research assistant)		
	Undergraduate Student		

Full details of individuals who have worked on the project:

Christopher A Buneo
Email: christopher.buneo@asu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: (b)(4), (b)(6) [redacted]
Contribution to the Project: Prov [redacted] ip and administration of the research project. Also supervised and trained one PhD student (Phataraphruk).
Funding Support: (b)(4), (b)(6) [redacted]
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Email (b) (6) [redacted]
Most Senior Project Role: Technician
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Assistance with animal handling and training.
Funding Support: (b)(4), (b)(6) [redacted].
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Most Senior Project Role: Technician
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Provided veterinary care to the animals; trained animals; trained graduate student, other technician and undergraduate student.
Funding Support: (b)(4), (b)(6) [redacted].
International Collaboration: No
International Travel: No

(b) (4) [redacted]
Most Senior Project Role: Technician
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Pro [redacted] to the animals; trained animals; trained graduate student, other technician and undergraduate student.
Funding Support: (b)(4), (b)(6) [redacted]
International Collaboration: No
International Travel: No

Preyaporn Phatarphruk
Email: pphatara@asu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of animals, training of technician and undergraduate student, installation of motion tracking system and virtual reality training platform.
Funding Support: NSF IGERT fellowship.
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Master's student involved in the training of animals and providing assistance to vet tech/lab manager and PhD student.
Funding Support: None.
International Collaboration: No
International Travel: No

(b) (6) [redacted]

Most Senior Project Role: Unde[redacted]nt
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of animals; providing assistance to vet tech/lab manager and graduate student.
Funding Support: None.
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
New York University	Academic Institution	New York City

Full details of organizations that have been involved as partners:

New York University
Organization Type: Academic Institution
Organization Location: New York City
Partner's Contribution to the Project:
In-Kind Support
Collaborative Research
More Detail on Partner and Contribution: New York University is the home institution of B jan Pesaran, the co-PI/PD on the project.

What other collaborators or contacts have been involved?

Bijan Pesaran, New York University. As a co-PI/PD on the project, Dr. Pesaran will be submitting his own progress report.

Back to the top

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The proposed research has significant potential to impact our understanding of basic neural processes such as multisensory integration, state estimation, and sensorimotor control while also advancing the fundamental engineering knowledge necessary to create the next generation of brain-machine interfaces (BMIs). Next generation BMIs for replacing lost limb function are envisioned to support the integration of artificial somatosensory feedback (tactile/proprioceptive) with natural vision (Bensmaia and Miller, 2014). The feasibility of such systems has already been established using monkey models (Shokur et al., 2013; Dadarlat et al., 2015). Optimizing these systems however will depend critically on understanding how natural visual and somatosensory signals interact within and among multisensory brain areas and their associated neural networks. Here we will address this knowledge gap by quantifying changes in spiking, local field potential (LFP) activity and neural coherence that result from integration of natural visual and somatosensory signals generated during arm movements. This will be performed in frontal and parietal brain areas of the monkey that have been implicated in sensorimotor control of the arm. The joint analysis of spiking and local field potential activity measured at different sites in the brain offers a unique opportunity to examine functional interactions between neurons and ensembles of neurons across large-scale brain networks. Spike-field coherence is a measure of association using these signals that links different scales: ~10-50um for spiking activity and ~200-500um for local field potential activity. This provides a bridge to less invasive measures of neural activity such as electrocorticography on the surface of the brain and EEG non-invasively at the scalp.

Optimizing multisensory BMIs will also require understanding how perceptual and action-related brain representations evolve as subjects learn to use and ultimately embody these devices. Current state-of-the-art robotic devices are not yet capable of the real-time, high-dimensional, natural movements that are likely necessary for embodiment (Putrino et al.,2015). Even if such devices were currently available, other factors would likely make them impractical for patients to use without extensive training. Virtual devices however offer a safe and practical alternative to robotic ones, allowing a multitude of behaviors to be learned and trained (Bohil et al., 2011; Putrino et al., 2015). Precisely how realistic such environments need to be to enable embodiment is unclear; diverse virtual stimuli have been used in different studies, with no attempt to determine the optimal (or minimal) stimulus for enabling embodiment. The studies proposed here, which involve virtual reaching tasks that vary the degree of reliability and semantic information about limb structure, will provide critical insights in this regard. This information will in turn advance the development of BMIs and related assistive technologies designed to improve the quality of life of individuals with sensorimotor disabilities.

What is the impact on other disciplines?

The VR system developed here for non-human primates can easily be duplicated for use in studies of human sensorimotor control and perception, including in the PI's own human motor control lab at Arizona State University.

What is the impact on the development of human resources?

During the last period the project provided research and training opportunities for one PhD student, one Master's student and one undergraduate student. Two of these students are from traditionally underrepresented groups. All students have been exposed to animal training and handling and well as motion capture and virtual reality techniques. In addition, the PhD student has received additional training in basic surgical techniques.

What is the impact on physical resources that form infrastructure?

The project has led to the rebuilding of the PI's non-human primate laboratory at Arizona State University. This facility is designed for the acquring and analyzing behavioral and neural data in non-human primates and is available for use by the PI and his collaborators at ASU.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

Nothing to report.
Back to the top

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

1) We have experienced a delay in hiring a postdoctoral fellow for the project as a suitable candidate could not be found. We will be interviewing another candidate during the last week of November. If we are not succesful in recruiting this person, we will begin exploring the option of hiring another PhD student instead.

2) Integrating the new motion capture system and VR engine into our behavioral control system proved more difficult than we anticipated, which delayed progress. However, most of the major issues have been overcome such that we have are now able to train animals with this system.

3) In our experience, some animals have difficulty working in the VR environment and we anticipate that may also be the case in this project. If this proves to be the case we will look to simplify the tasks and if necessary replace animals with others if the these hurdles prove to be insurmountable.

Changes that have a significant impact on expenditures

As described above, we have experienced a delay in hiring a postdoctoral fellow for the project as a suitable candidate could not be found. We will be interviewing another candidate during the last week of November. If we are not succesful in recruiting this person, we will begin exploring the option of hiring another PhD student instead.

In addition, the PhD student working on the project had one year of eligibility left on a NSF IGERT fellowship and received much of her support during the last project period from that grant, which also affected expenditures.

Significant changes in use or care of human subjects

Nothing to report.

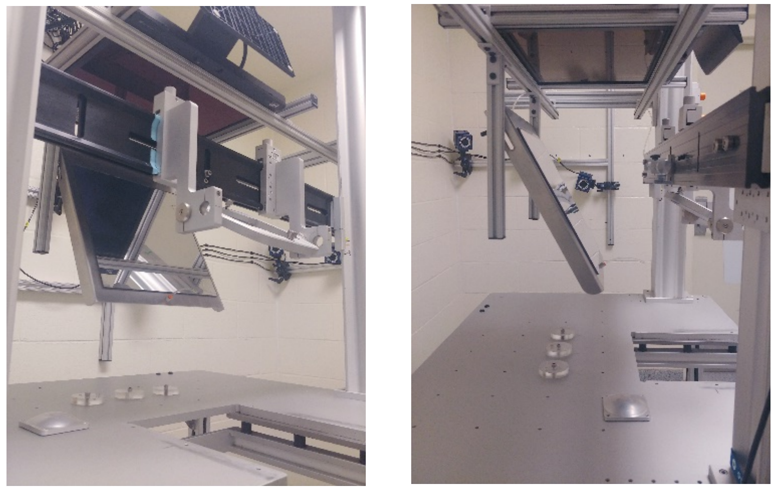
Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.
Back to the top

Figure 1. Oblique (A) and side (B) views of the tabletop and projection system, including the display mirror. Animal's chair is positioned at the cutout in the table and the animal initially positions their hand at one of three locations on the tabletop, indicated by the circular plastic discs. The VR environment is displayed on a 3D monitor (oriented horizontally above the tabletop) and projected onto the mirror in front of the animal.



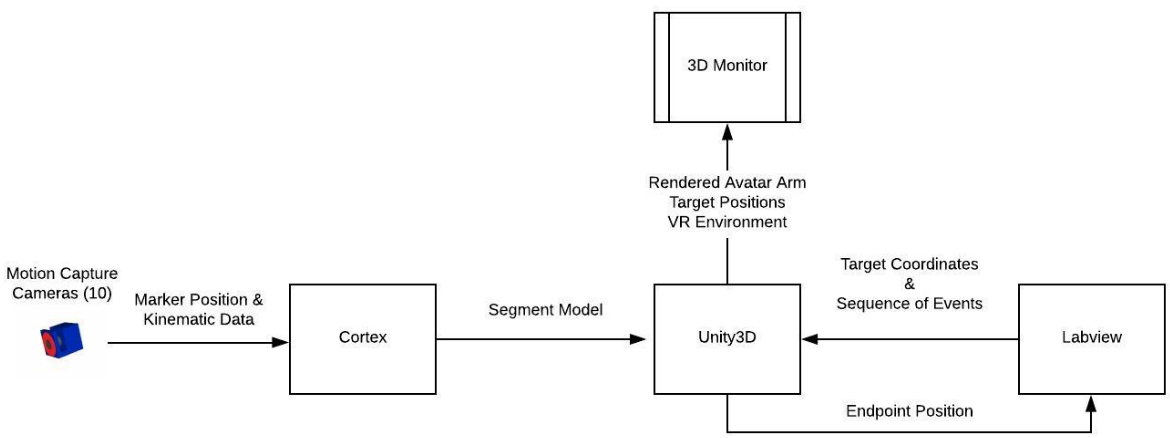


Figure 2. Diagram of the VR-based behavioral control system. Cortex records the marker positions and uses Calcium Solver, a built in skeletal engine, to generate a segment model which is streamed to Unity to animate a custom avatar (created in Maya). Labview controls the sequence of events on a given trial, including sending the coordinates of reach targets to Unity for rendering. Unity, in addition to rendering the avatar, targets, and other components of the VR environment, sends the current position of the endpoint of the arm to Labview to allow for checking of arm position against target position, allowing the task to proceed and for behavioral reinforcement to occur.

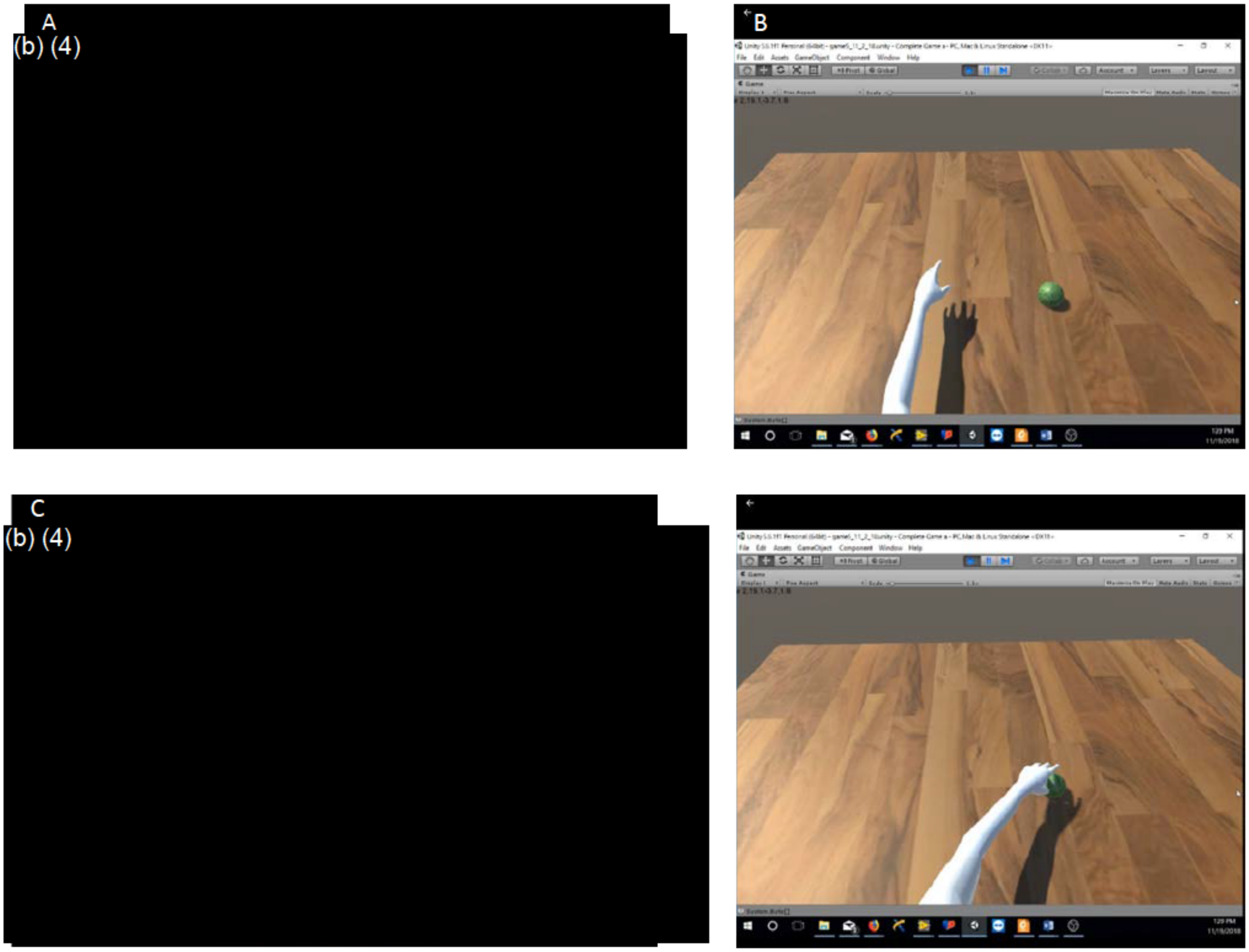


Figure 3. Sequence of events on a single trial. A. Left: Video capture of the animal viewing the display mirror, with his arm to the right of his body and his hand contacting a plastic disc embedded in the table. To the right is a ball and stick representation of the animal's arm as viewed in Cortex (the motion capture software). B. Simultaneous view of the VR display. The view is left-right reversed relative to what the animal sees as a consequence of the mirror used in the projection system. In this video frame, a leftward target (green sphere) has been presented but appears to the right of the animal's arm. C. Same view as in A but following movement to the target. Animal's hand is now to the left of his body in both the video and Cortex display. D. Simultaneous view of the VR display, showing the arm at the target.

Project Report Printer Friendly Version

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Preview of Award 1557886 - Annual Project Report

Cover | Accomplishments | Products | Participants/Organizations | Impacts | Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	**4900**
Federal Grant or Other Identifying Number Assigned by Agency:	**1557886**
Project Title:	**Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
PD/PI Name:	**Bijan Pesaran, Principal Investigator**
Recipient Organization:	**New York University**
Project/Grant Period:	**09/15/2016 - 08/31/2021**
Reporting Period:	**09/01/2017 - 08/31/2018**
Submitting Official (if other than PD\PI):	**Bijan Pesaran** **Principal Investigator**
Submission Date:	**08/15/2019**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Bijan Pesaran**

Back to the top

Accomplishments

*** What are the major goals of the project?**

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the

relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:	Our major activity this reporting period has been to develop and deploy the virtual reality environment and motion capture technology for use by the Buneo lab in their experiments.
Specific Objectives:	To perform the experiments necessary for this proposal, we must render an avatar in virtual reality that is based on the anatomically correct movements of a non-human primate upper limb extremity. The limb is concurrently being tracked by a motion capture system using cameras that detect and localize in space retroreflective markers placed on the limb. To render the avatar we must track the markers in real-time with low latency, < 20 ms, compute the pose of the limb by solving the skeletal model for the animal, and then render the avatar given the skeletal pose.
Significant Results:	We have successfully deployed an avatar that captures the anatomical degrees of freedom in the arm and wrist up to but not including detailed finger movements. This system is being used to perform animal training in the Buneo lab.
Key outcomes or Other achievements:	We have enabled experiments and behavioral control interface based on an anatomically correct avatar in virtual reality.

*** What opportunities for training and professional development has the project provided?**

An undergraduate student, [redacted], has worked on the project to develop and deploy the virtual reality technolgy. She has learned about computer-aided design and how to develop solid models in software we use - Maya and 3DSmax. [redacted] has also learned the principles of visual-spatial animal behavior and perception. This impacts the features of the virtual reality arena and avatar that need to be accurate to drive spatial percepts necessary for the animal to perform the virtual task successfully.

*** How have the results been disseminated to communities of interest? If so, please provide details.**

We have not disseminated the work outside of our collaborative arrangement as part of this project.

*** What do you plan to do during the next reporting period to accomplish the goals?**

In the next reporting period, we will extend the virtual reality environment to incorporate visual eye mvoement tracking as well as any other innovations necessary to perform the behavioral training. We will also support neurophysiological data analysis as the recordings become available.

We will train a to-be-named student at NYU in the technology to be disseminated and how the technology dissemination depends on the psychology of spatial perception.

Back to the top

Products

Books

Nothing to report.

Book Chapters

Nothing to report.

Inventions

Nothing to report.

Journals or Juried Conference Papers

Nothing to report.

Licenses

Nothing to report.

Other Conference Presentations / Papers

Nothing to report.

Other Products

Nothing to report.

Other Publications

Nothing to report.

Patent Applications

Nothing to report.

Technologies or Techniques

Nothing to report.

Thesis/Dissertations

Nothing to report.

Websites or Other Internet Sites

Nothing to report.

Back to the top

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Pesaran, Bijan	PD/PI	(b)(4), (b)(6) [redacted]
(b) (6) [redacted]	Undergraduate Student	[redacted]

Full details of individuals who have worked on the project:

Bijan Pesaran
Email: bijan@nyu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: [redacted]
Contribution to the Project: Design experiments and analyze data. Oversee project.
Funding Support: None
International Collaboration: No
International Travel: No

[redacted]
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: [redacted]
Contribution to the Project: Assisted with experimental design.
Funding Support: None
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Christopher Buneo	Academic Institution	Phoenix, Arizona

Full details of organizations that have been involved as partners:

Christopher Buneo
Organization Type: Academic Institution
Organization Location: Phoenix, Arizona
Partner's Contribution to the Project:
Collaborative Research
More Detail on Partner and Contribution:

What other collaborators or contacts have been involved?

Nothing to report

Back to the top

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The proposed research has significant potential to impact our understanding of basic neural processes such as multisensory integration, state estimation, and sensorimotor control while also advancing the fundamental engineering knowledge necessary to create the next generation of brain-machine interfaces (BMIs). Next generation BMIs for replacing lost limb function are envisioned to support the integration of artificial somatosensory feedback (tactile/proprioceptive) with natural vision (Bensmaia and Miller, 2014). The feasibility of such systems has already been established using monkey models (Shokur et al., 2013;

Dadarlat et al., 2015). Optimizing these systems however will depend critically on understanding how natural visual and somatosensory signals interact within and among multisensory brain areas and their associated neural networks. Here we will address this knowledge gap by quantifying changes in spiking, local field potential (LFP) activity and neural coherence that result from integration of natural visual and somatosensory signals generated during arm movements. This will be performed in frontal and parietal brain areas of the monkey that have been implicated in sensorimotor control of the arm. The joint analysis of spiking and local field potential activity measured at different sites in the brain offers a unique opportunity to examine functional interactions between neurons and ensembles of neurons across large-scale brain networks. Spike-field coherence is a measure of association using these signals that links different scales: ~10-50um for spiking activity and ~200-500um for local field potential activity. This provides a bridge to less invasive measures of neural activity such as electrocorticography on the surface of the brain and EEG non-invasively at the scalp.

Optimizing multisensory BMIs will also require understanding how perceptual and action-related brain representations evolve as subjects learn to use and ultimately embody these devices. Current state-of-the-art robotic devices are not yet capable of the real-time, high-dimensional, natural movements that are likely necessary for embodiment (Putrino et al., 2015). Even if such devices were currently available, other factors would likely make them impractical for patients to use without extensive training. Virtual devices however offer a safe and practical alternative to robotic ones, allowing a multitude of behaviors to be learned and trained (Bohil et al., 2011; Putrino et al., 2015). Precisely how realistic such environments need to be to enable embodiment is unclear; diverse virtual stimuli have been used in different studies, with no attempt to determine the optimal (or minimal) stimulus for enabling embodiment. The studies proposed here, which involve virtual reaching tasks that vary the degree of reliability and semantic information about limb structure, will provide critical insights in this regard. This information will in turn advance the development of BMIs and related assistive technologies designed to improve the quality of life of individuals with sensorimotor disabilities.

What is the impact on other disciplines?

Nothing to report.

What is the impact on the development of human resources?

This project has contributed to human resource development by providing research and training opportunities for an undergraduate student in motion capture and virtual reality experiments.

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

Nothing to report.
Back to the top

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.
Back to the top

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Project Report Printer Friendly Version

Preview of Award 1558151 - Annual Project Report

Cover | Accomplishments | Products | Participants/Organizations | Impacts | Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	**4900**
Federal Grant or Other Identifying Number Assigned by Agency:	**1558151**
Project Title:	**Collaborative Research: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
PD/PI Name:	**Christopher A Buneo, Principal Investigator**
Recipient Organization:	**Arizona State University**
Project/Grant Period:	**09/15/2016 - 08/31/2021**
Reporting Period:	**09/01/2018 - 08/31/2019**
Submitting Official (if other than PD\PI):	**Christopher A Buneo Principal Investigator**
Submission Date:	**08/16/2019**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Christopher A Buneo**

Back to the top

Accomplishments

*** What are the major goals of the project?**

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations

interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Major activities included 1) Recruitment and training of lab personnel, 3) Enhancement of the virtual reality training platform that will be used to accomplish all of the project's objectives, 3) Acquisition and training of animals, 4) Development of behavioral analyses of animal movement trajectories and endpoints, 5) Acquisition and installation of a multichannel neural recording system.

Specific Objectives:

The specific objectives of the project include 1) Characterizing the effect of varying semantic information about limb structure on oscillatory and spiking activity within multimodal cortical areas during arm state estimation, 2) Elucidating changes in oscillatory and spiking activity within multimodal cortical areas as a function of changes in the relative reliability of visual and somatic position cues and 3) Characterizing changes in functional connectivity among multimodal cortical areas as a function of changes in semantic information and sensory reliability.

During the current reporting period progress was made toward meeting these objectives by refining the VR environment that will be used to alter visual reliability and semantic information. In addition, animals were trained to move in this environment with under strict spatial and temporal constraints - this is required to characterize neural activity in areas involved in representing arm posture and movement. The results of these activities are described in more detail under 'Significant Results'.

Significant Results:

1) We have enhanced the VR environment initially created in Year 2 (see Supporting Documentation, Figure 3) by creating a room that closely resembles the actual room where the animals perform their behavioral tasks. This is critical as responses to manipulation of visual reliability and semantics will depend strongly on the animal's belief that the environment in which it is interacting is veridical. As a result the virtual environment must appear as similar as possible to the real one, which has been achieved.

2) We have created three new avatar arms that will be used during the recording experiments. One arm is a rhesus macacque monkey arm, which will be used for training and for the initial experiments involving manipulations of visual reliability. The other arms were created to resemble 1) a human arm, and 2) a prosthetic arm, based on the LUKE arm by Mobius Bionics (http://www.mobiusbionics.com/luke-arm/), a commercially available prosthetic arm based on the DARPA/DEKA arm. The three arms will be

used on different recording days, in order to initially assess the effects of semantic manipulations on multisensory integration. These additions to the VR environment are shown in the supporting documentation, Figures 4 through 7. A separate MP4 files showing an animal reaching to virtual targets using the monkey avatar arm is availalble offline upon request (video files cannot be uploaded to Reporting.Research.Gov.

3) We have developed methods to manipulate the visual reliability of the virtual arms by 'blurring' them with respect to other objects in the environment. In addition, this blurring can also now be performed on a trial-by-trial basis via a command sent by LabVIEW to the virtual environment. Examples of the blurring effect can be seen in Figures 8 through 10. In addition, a separate MP4 file showing the blurring effect implemented on a trial-by-trial basis is also available offiine upon request.

4) We have also developed methods to analyze movement variability resulting from manipulations of visual reliabilty. Our initial predictions are that altering the reliability of the visual information about arm position will alter the relative weighting of vision and proprioception, changing both the neural responses in areas associated with the representation of arm position and as well as the motor behavior of the animals. Behavioral changes that would be expected include alterations in the variability of initial movement directions and/or movement endpoints. As a result we have developed methods to quantify behavioral variability. An example of quantification of endpoint variability using principal components analysis and subsequent calculation of 95% confidence ellipsoids is shown in the supporting documenation, Figure 11.

5) A second animal has been acquired and has begun training in the virtual environment.

6) A new multichannel neural recording system was acquired and installed and is now ready for use.

Key outcomes or Other achievements:

1) Hiring of a research scientist and recruitment of a female undergraduate student to work on the project. The research scientist was previously employed at (b) (6) [redacted].

2) Significant enhancements to the virtual environment in which the animals interact, as described in more detail above (see Significant Results 1-3).

3) Methods have been developed to analyze key features of the animals' behavior.

4) A second animal has been acquired and begun training on versions of the VR task that will used during neural recordings.

5) The multichannel system that will be used to record neural data was acquired and installed.

*** What opportunities for training and professional development has the project provided?**

During the last project period the project has enhanced the mentoring of 1 research scientist, 1 PhD student (female), 1 Master's students, 1 lab technician (female), 1 lab manager/animal technician (female), and 2 undergraduate students (1 female).

Training and professional development activities included direct instruction by 1) the PI to the PhD student and research scientist and 2) the PhD student and research scientist to the other students and technicians. Students received mentoring through weekly small group meetings and regular lab meetings of all the PIs students. Students also attended relevant seminars on campus. The PhD student also attended the 2018 Annual Meeting of the Society for Neuroscience, which was important for her professional development.

*** How have the results been disseminated to communities of interest? If so, please provide details.**

1) Via outreach to neighboring higher education institutions in the greater Phoenix area. For example, in December of 2018 the PI gave a lecture to a group of physical therapy students at Northern Arizona University entitled “Neural Interfaces and their relevance to rehabilitation”. This lecture included a discussion of the current project and is implications for development of virtual reality-based methods for training patients to use advanced prostheses. This lecture will be given again in Fall 2019.

2) Via lectures at the PI's home institution. For example, the PI coordinates a course every year for graduate students called 'Clinical Neuroscience' and devotes one lecture in this course to neural interfaces where he discusses in part the research activities covered in this grant. Students in this class come from various disciplines and for some this is the first exposure to the subject.

In addition, in the last couple of years the PI was involved in a public lecture series at ASU called 'Ethics@Twilight' where he serving on a panel presentation entitled “Advanced prostheses: Are research directions aligned with amputee preferences”. Implications of the current project and similar ones for training people to used advanced protheses was one of the discussion items. The audience was very diverse, with many being introduced to these topics for the first time.

Lastly, the PI speaks every year during several sections of an undergraduate course called 'ASU 101'. Students are all in their first year and are often unaware of research in advanced prosthetics systems (including the role of virtual reality) which I cover when I discuss my current research.

*** What do you plan to do during the next reporting period to accomplish the goals?**

During the next reporting period we plan to do the following:

1) Complete building of experimental apparatus, including the VR environment.
2) Complete training of the first two animals on tasks related to Aim 1.

3) Initiate and complete behavioral analyses of tasks related to Aim 1 in the first animal.

4) Implant first animal with microelectrode arrays and begin addressing the specific objectives of Aim 1 in this

animal.
5) To enhance Broader impacts, recruit additional undergraduates to be involved in the project and encourage them and other students to participate in colloquia addressing the ethical, societal and policy implications of neuroscience research.

Supporting Files

	Filename	Description	Uploaded By	Uploaded On
(Download)	Supporting_Documentation.pdf	File containing figures referenced in the Accomplishment section.	Christopher Buneo	08/14/2019

Back to the top

Products

Books

Book Chapters

Christopher A. Buneo Preyaporn Phataraphruk Paul VanGilder (2019). Neural Representations of Intended Movement.. *Reference Module in Neuroscience and Biobehavioral Psychology* Elsevier. https://doi.org/10.1. Status = PUBLISHED; Acknowledgement of Federal Support = No ; Peer Reviewed = No

Inventions

Journals or Juried Conference Papers

Preyaporn Phataraphruk Qasim Rahman Kishor Lakshmi Narayanan Mitchell Fruchtman Christopher Buneo (2019). Effects of Arm Configuration on Patterns of Reaching Variability. *PLoS One*. . Status = OTHER; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses

Other Conference Presentations / Papers

Preyaporn Phataraphruk Qasim Rahman Kishor Lakshmi Narayanan Mitchell Fruchtman Christopher Buneo (2019). *Effects of initial arm posture on reach endpoint variability.*. Annual Meeting of the Society for Neuroscience. Chicago. Status = ACCEPTED; Acknowledgement of Federal Support = Yes

Amanda Knight Preyaporn Phataraphruk (2019). *Optimizing Success in NHP work with Individualized Problem Solving Strategies*. Annual Meeting of The American Association for Laboratory Animal Science. Denver. Status = ACCEPTED; Acknowledgement of Federal Support = Yes

Other Products

Seminar.
Seminar given to physical therapy faculty and students at Northern Arizona University, Phoenix campus: "Neural Interfaces and their relevance to rehabilitation". Fall 2018, Northern Arizona University, Phoenix, AZ, December 2018.
This lecture included a discussion of the current project and is implications for development of virtual reality-based methods for training patients to use advanced prostheses.

Seminar.
Panel presentation delivered to the general public as part of the Ethics@Twilight lecture series: "Advanced prostheses: Are research directions aligned with amputee preferences". Fall 2017 lecture series, Ethics @ Twilight, Arizona State University, Tempe, AZ, September 2017.
Implications of the current project and similar ones for training people to used advanced protheses was one of the discussion items.

Other Publications

Patent Applications

Technologies or Techniques

Thesis/Dissertations

Websites or Other Internet Sites

Back to the top

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked

Buneo, Christopher	PD/PI	(b)(4), (b)(6) [redacted]	
(b) (6) [redacted]	Graduate Student (research assistant)		
	Undergraduate Student		
	Undergraduate Student		
	Technician		
	Technician		
VanGilder, Paul	Staff Scientist (doctoral level)		
Phatarphruk, Preyaporn	Graduate Student (research assistant)		

Full details of individuals who have worked on the project:

Christopher A Buneo
Email: christopher.buneo@asu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Provided overall leadership and administration of the research project. Also supervised and trained one PhD student (Phataraphruk) and one research scientist (VanGilder).
Funding Support: (b)(4), (b)(6) [redacted]
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Master's student involved in the training of animals and providing assistance to vet tech/lab manager and PhD student.
Funding Support: None.
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Most Senior Project Role: Unde [redacted]
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of animals; providing assistance to vet tech/lab manager and graduate student.
Funding Support: None.
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of animals; providing assistance to vet tech/lab manager and graduate student.
Funding Support: (b)(4), (b)(6) [redacted].
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Email: (b) (6) [redacted]
Most Senior Project Role: Technician
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Provided assistance to students and other staff with animal handling and training.
Funding Support: (b)(4), (b)(6) [redacted].
International Collaboration: No
International Travel: No

(b) (6) [redacted]
Email: [redacted]
Most Senior Project Role: Technician

Nearest Person Month Worked: [redacted]
Contribution to the Project: Provided veterinary care to the animals; trained animals; trained graduate student, other technician and undergraduate student.
Funding Support: [redacted].
International Collaboration: No
International Travel: No

Paul VanGilder
Email: pvangild@asu.edu
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: [redacted]
Contribution to the Project: Provided assistance with coding of experimental paradigm; installed neural recording system; trained animals.
Funding Support: [redacted].
International Collaboration: No
International Travel: No

Preyaporn Phatarphruk
Email: pphatara@asu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: [redacted]
Contribution to the Project: Trained animals; trained technician and undergraduate student in setup of motion capture system and LabVIEW behavioral control programs; installed motion tracking system and virtual reality training platform; developed behavioral control system; created virtual avatars for use in animal training.
Funding Support: None.
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
New York University	Academic Institution	New York City

Full details of organizations that have been involved as partners:

New York University
Organization Type: Academic Institution
Organization Location: New York City
Partner's Contribution to the Project:
In-Kind Support
Collaborative Research
More Detail on Partner and Contribution: New York University is the home institution of B jan Pesaran, the co-PI/PD on the project.

What other collaborators or contacts have been involved?

[redacted] has been contracted to assist in refining the VR environment used in the current experiments.

Back to the top

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The VR environment that was developed during this reporting period will allow unprecedented characterization of multisensory integration in the primate brain. Previous investigations of visual-somatic integration in primates used either fake monkey arms or virtual stimuli that did not adequately resemble a real monkey arm. The arms and environment developed here will all

The VR environment developed here will also impact development and use of multisensory BMIs. Although it is clear that virtual training environments can provide a safe and practical alternative to physical environment for subjects leaning to use anthropomorphic robotic devices, precisely how realistic such environments need to be to enable embodiment is unclear. The system that has been developed here, which can switch between multiple avatar arms while also altering their visual properties, could provide critical insights into this important question. In addition, through its ability to alter visual properties of the limb (and potentially other parts of the environment), the system could provide critical information regarding the use of multisensory BMIs in uncertain environments. This information will in turn advance the development of BMIs and related assistive technologies designed to improve the quality of life of individuals with sensorimotor disabilities.

What is the impact on other disciplines?

The VR system developed here for non-human primates can easily be duplicated for use in studies of human sensorimotor control and perception, as well as for human physical rehabilitation. Virtual reality has been used for years in both disciplines but as far as we are aware no existing system has the capabilities that we have developed and will continue to develop here.

What is the impact on the development of human resources?

During the last period the project provided research and training opportunities for one research scientist, one PhD student, one Master's student and two undergraduate student. Three of these students are from traditionally underrepresented groups. All students have been exposed to animal training and handling and well as motion capture and virtual reality techniques. In addition, the
PhD student has received additional training in basic surgical techniques. Training was provided in the forms direct instruction, seminars, journal clubs, and weekly or biweekly lab meetings.

Through the PI's public seminars and regular teaching duties, undergraduate and graduate college students, as well as members of the general public, have been exposed to discussions of BMIs and the role of virtual environments in their development and use.

What is the impact on physical resources that form infrastructure?

The project has led to the rebuilding of the PI's non-human primate laboratory at Arizona State University. This facility is designed for the acquiring and analyzing behavioral and neural data in non-human primates and is available for use by the PI and his collaborators at ASU.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

Nothing to report.
Back to the top

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

1) We had a delay in hiring a postdoctoral fellow for the project as a suitable candidate could not be found. This problem was resolved by hiring a research scientist, (b) (6), (b) (4) [redacted].
2) Integrating the new motion capture system and VR engine into our behavioral control system proved more difficult than we anticipated, which delayed progress. However, most of the major issues have been overcome such that we have been able to train animals with this system. There have been some additional delays associated with the upgrades to the VR (including integrating the new environment, arms, blurring etc.) but these are due to be completed the week of August 12th 2019.
3) As expected, animals have had difficulty learning to work with the motion capture system and the VR environment. However have made several changes to our training protocols over the course of the past year and believe we have overcome most of the major issues.

Changes that have a significant impact on expenditures

As described above, we recently hired a research scientist to work on the project. Although his salary support is greater than that of a typical postdoc, his support during the current period (b) (4), (b) (6) [redacted]. As a result I do not anticipate a significant impact on expenditures in the short term.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.
Back to the top

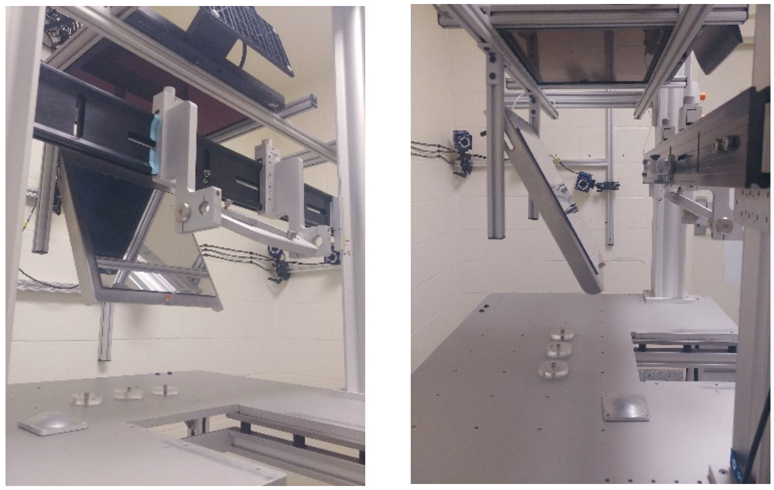

Figure 1. Oblique (A) and side (B) views of the tabletop and projection system, including the display mirror. Animal's chair is positioned at the cutout in the table and the animal initially positions their hand at one of three locations on the tabletop, indicated by the circular plastic discs. The VR environment is displayed on a 3D monitor (oriented horizontally above the tabletop) and projected onto the mirror in front of the animal.

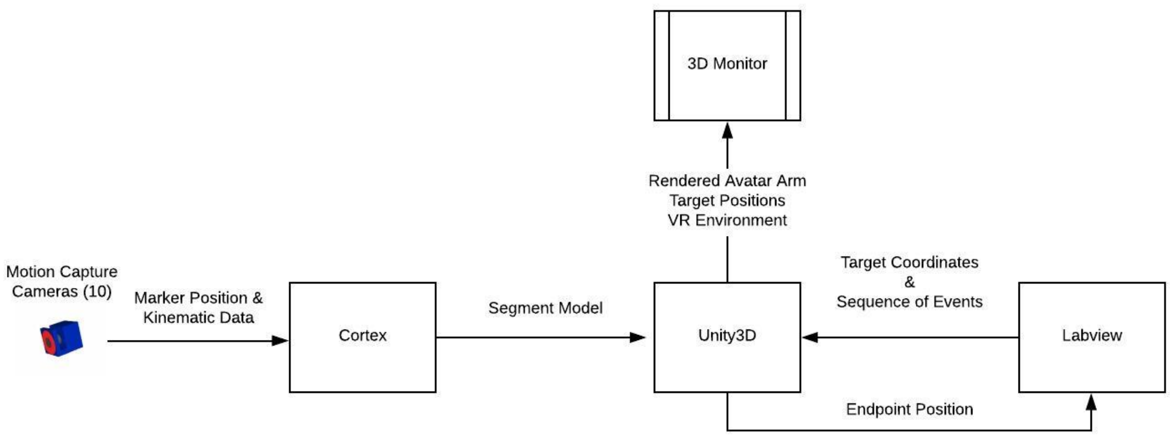

Figure 2. Diagram of the VR-based behavioral control system. Cortex records the marker positions and uses Calcium Solver, a built in skeletal engine, to generate a segment model which is streamed to Unity to animate a custom avatar (created in Maya). LabVIEW controls the sequence of events on a given trial, including sending the coordinates of reach targets to Unity for rendering. Unity, in addition to rendering the avatar, targets, and other components of the VR environment, sends the current position of the endpoint of the arm to LabVIEW to allow for checking of arm position against target position, allowing the task to proceed and for behavioral reinforcement to occur.

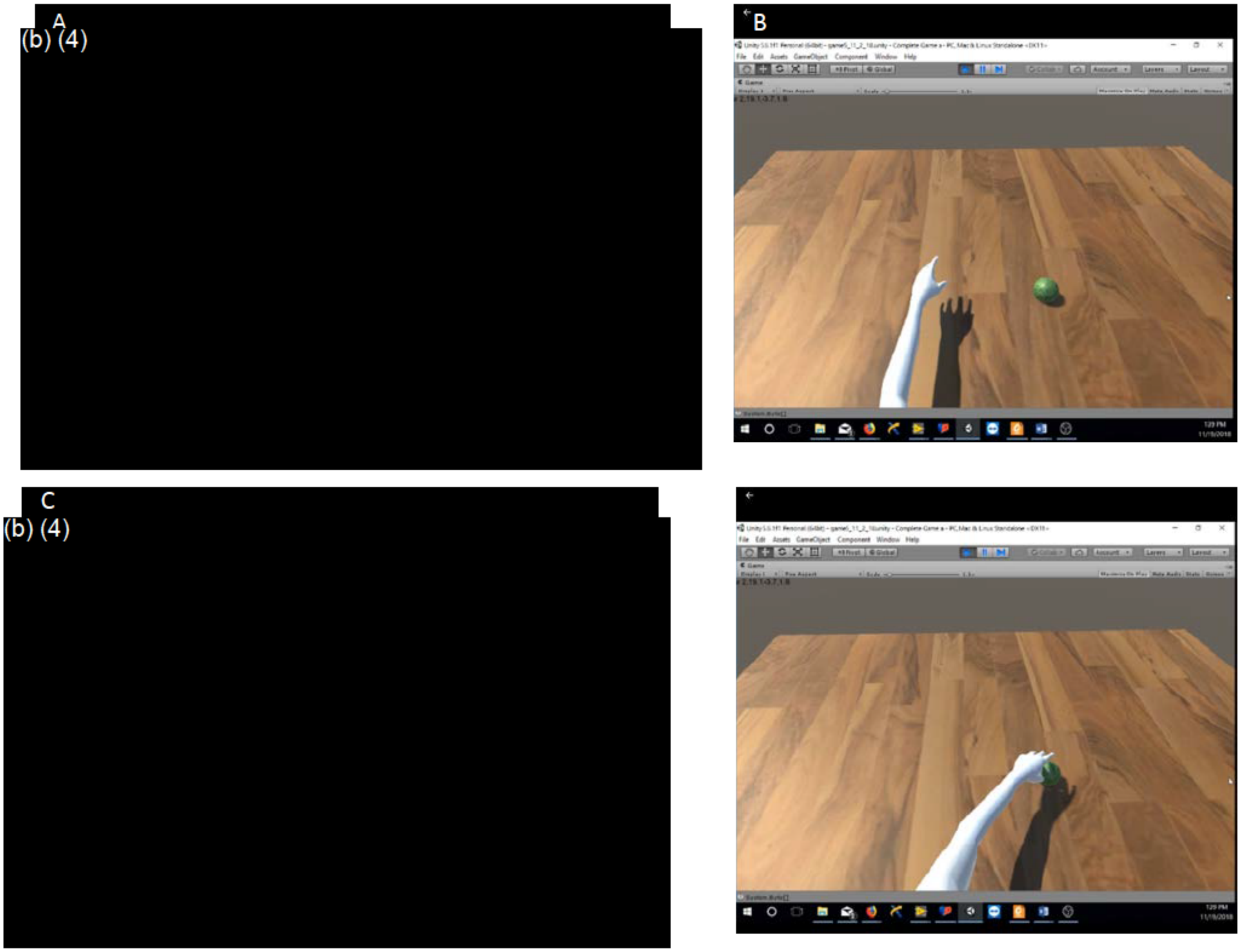

Figure 3. Sequence of events on a single trial. A. Left: Video capture of the animal viewing the display mirror, with his arm to the right of his body and his hand contacting a plastic disc embedded in the table. To the right is a ball and stick representation of the animal's arm as viewed in Cortex (the motion capture software). B. Simultaneous view of the VR display. The view is left-right reversed relative to what the animal sees as a consequence of the mirror used in the projection system. In this video frame, a leftward target (green sphere) has been presented but appears to the right of the animal's arm. C. Same view as in A but following movement to the target. Animal's hand is now to the left of his body in both the video and Cortex display. D. Simultaneous view of the VR display, showing the arm at the target.

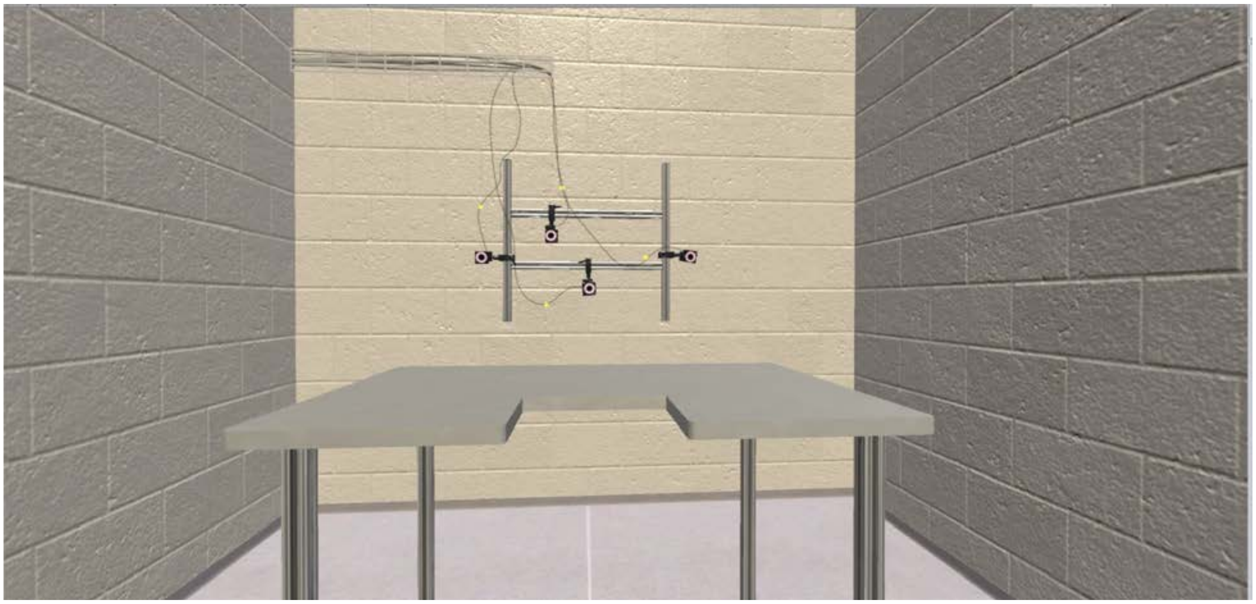

Figure 4. New VR environment created in collaboration with [redacted].

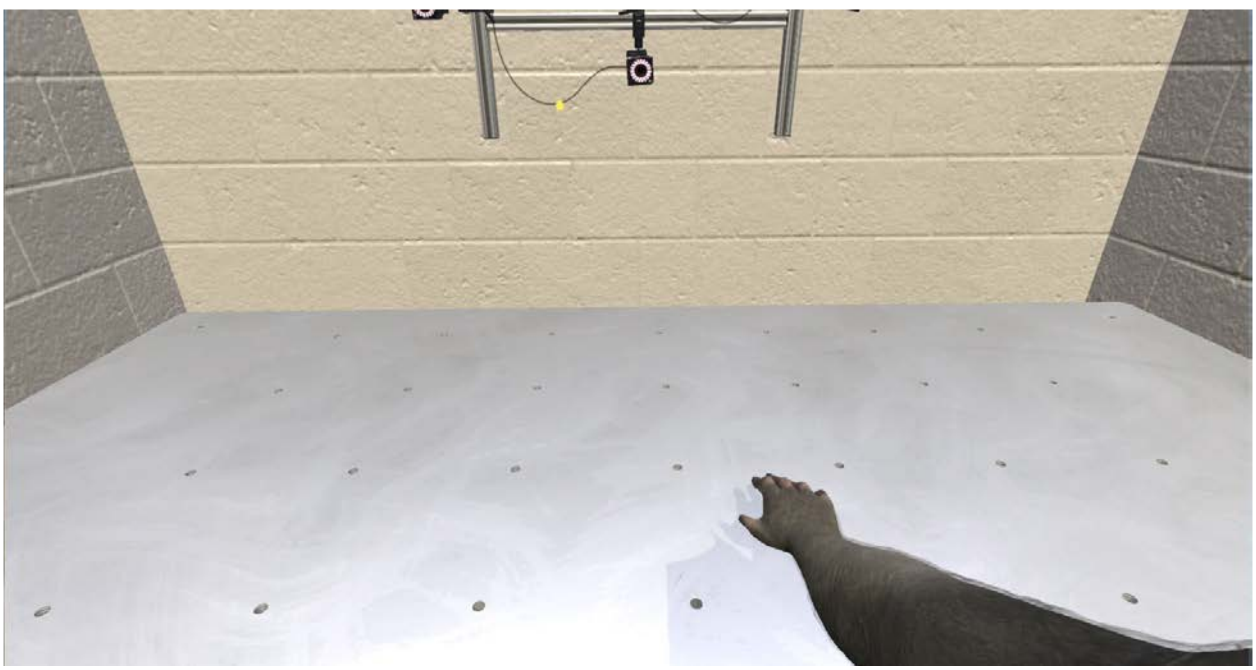

Figure 5. New VR environment viewed from an animal's perspective. Also shown is the rhesus macaque monkey avatar arm.

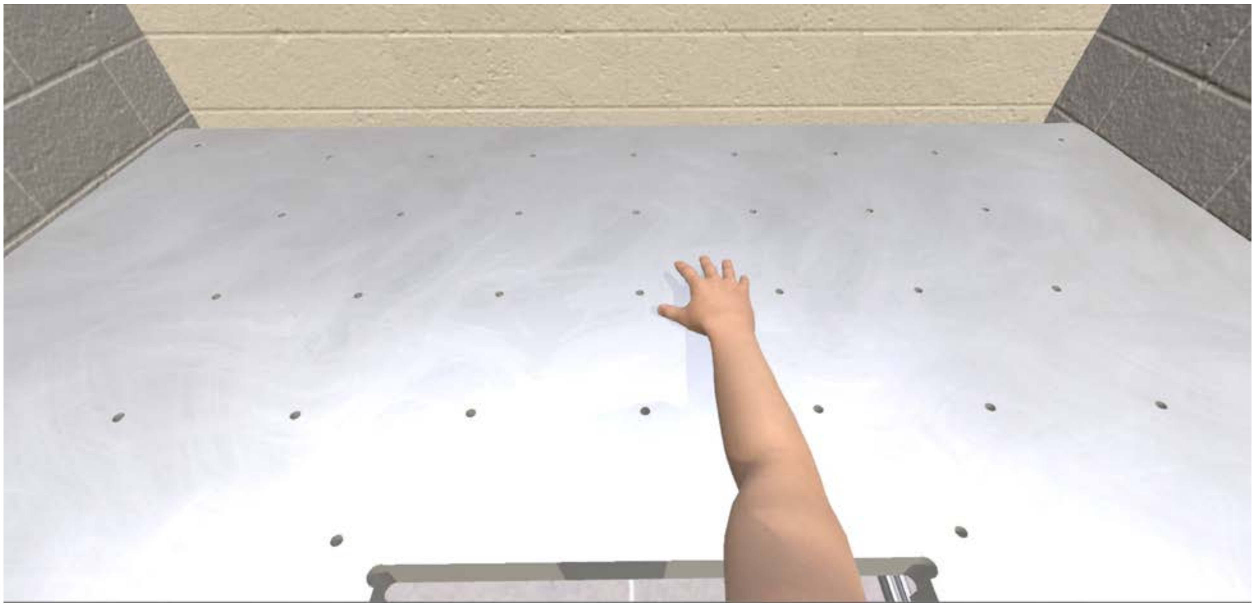

Figure 6. Human avatar arm.

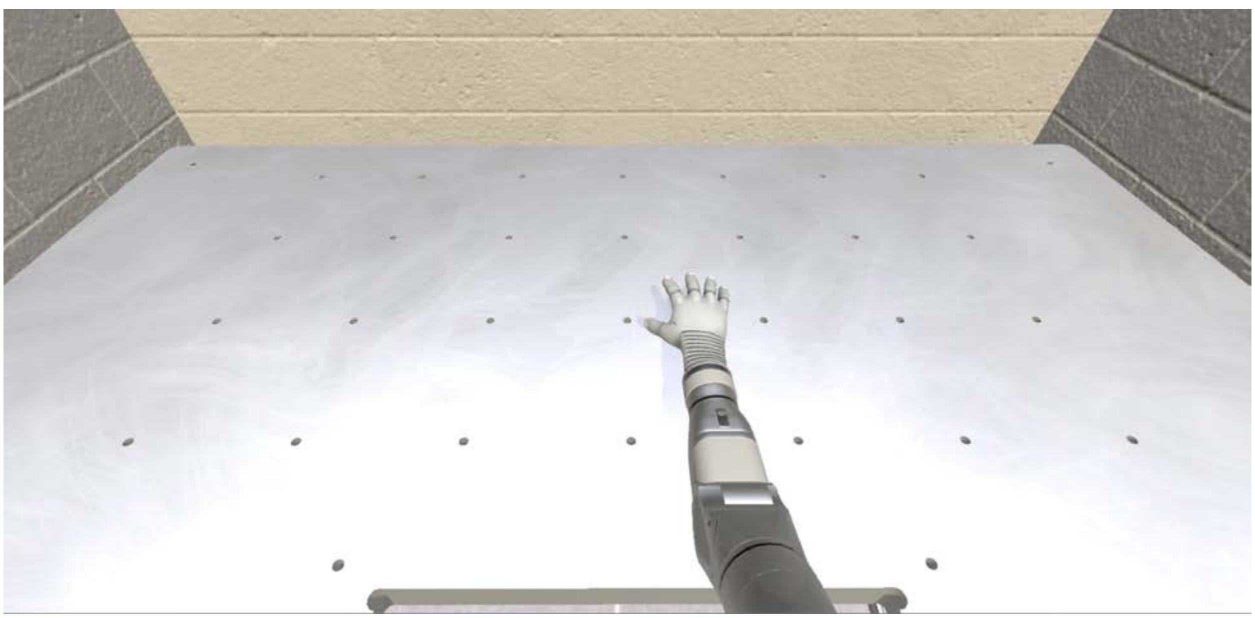

Figure 7. Robot avatar arm (i.e. prosthetic arm).

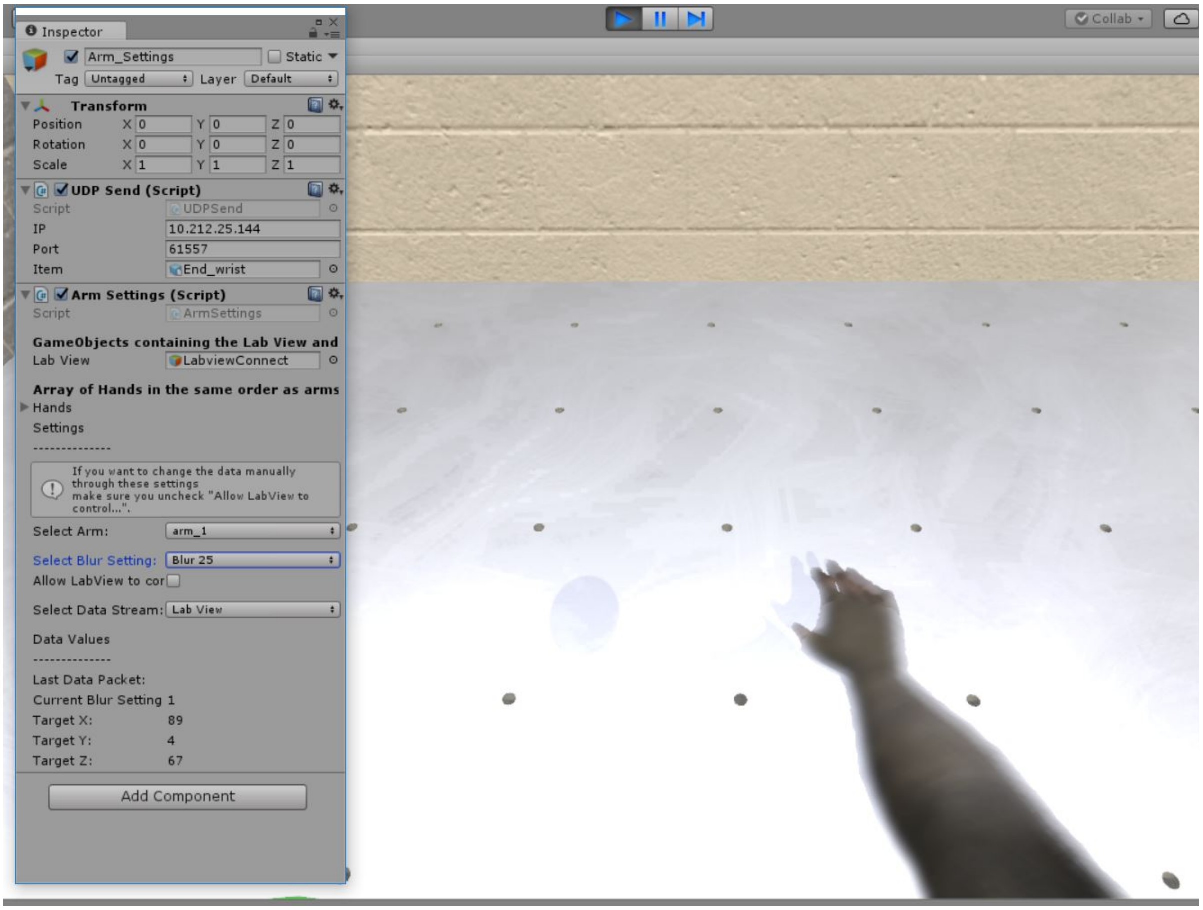

Figure 8. Rhesus macaque monkey avatar arm with 25% blurring. At the left is the Unity 3D interface for communicating with LabVIEW.

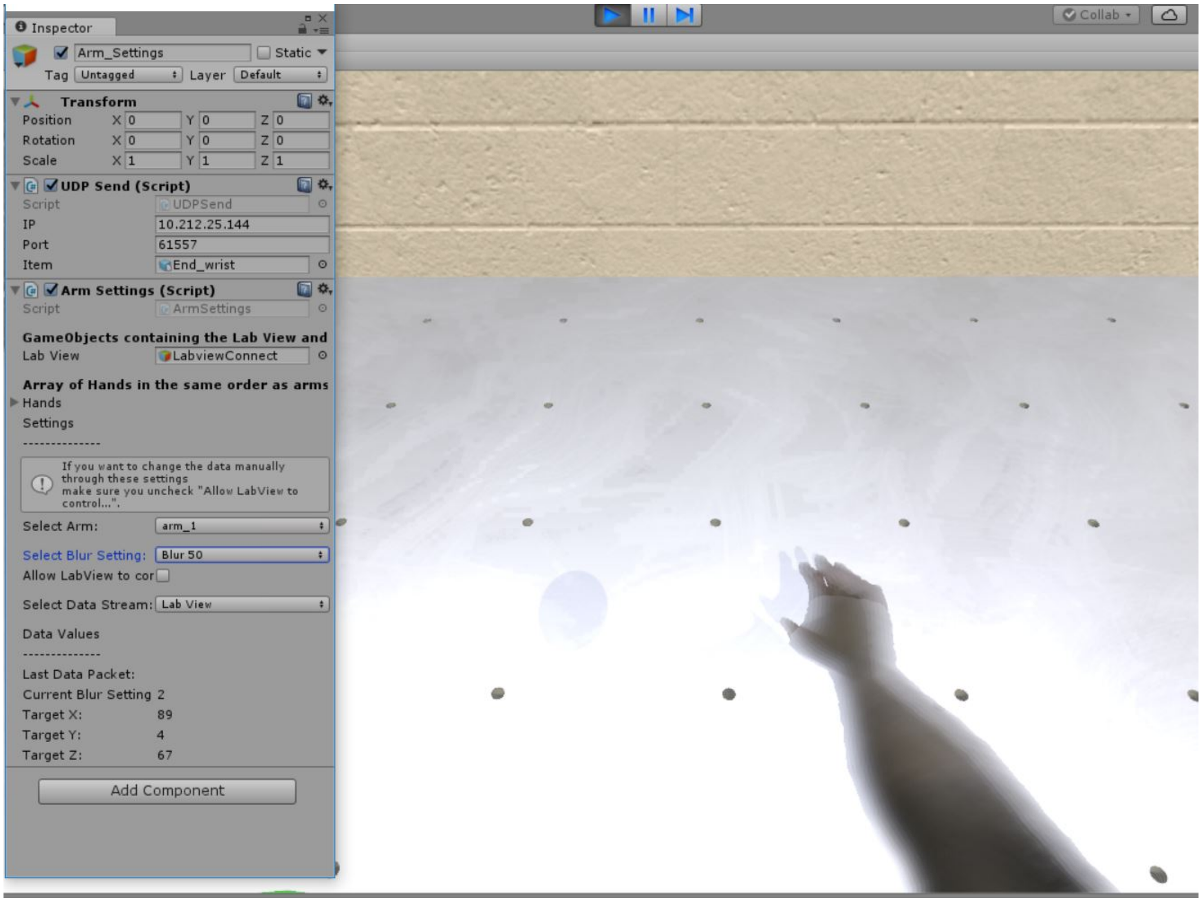

Figure 9. Rhesus macaque monkey avatar arm with 50% blurring.

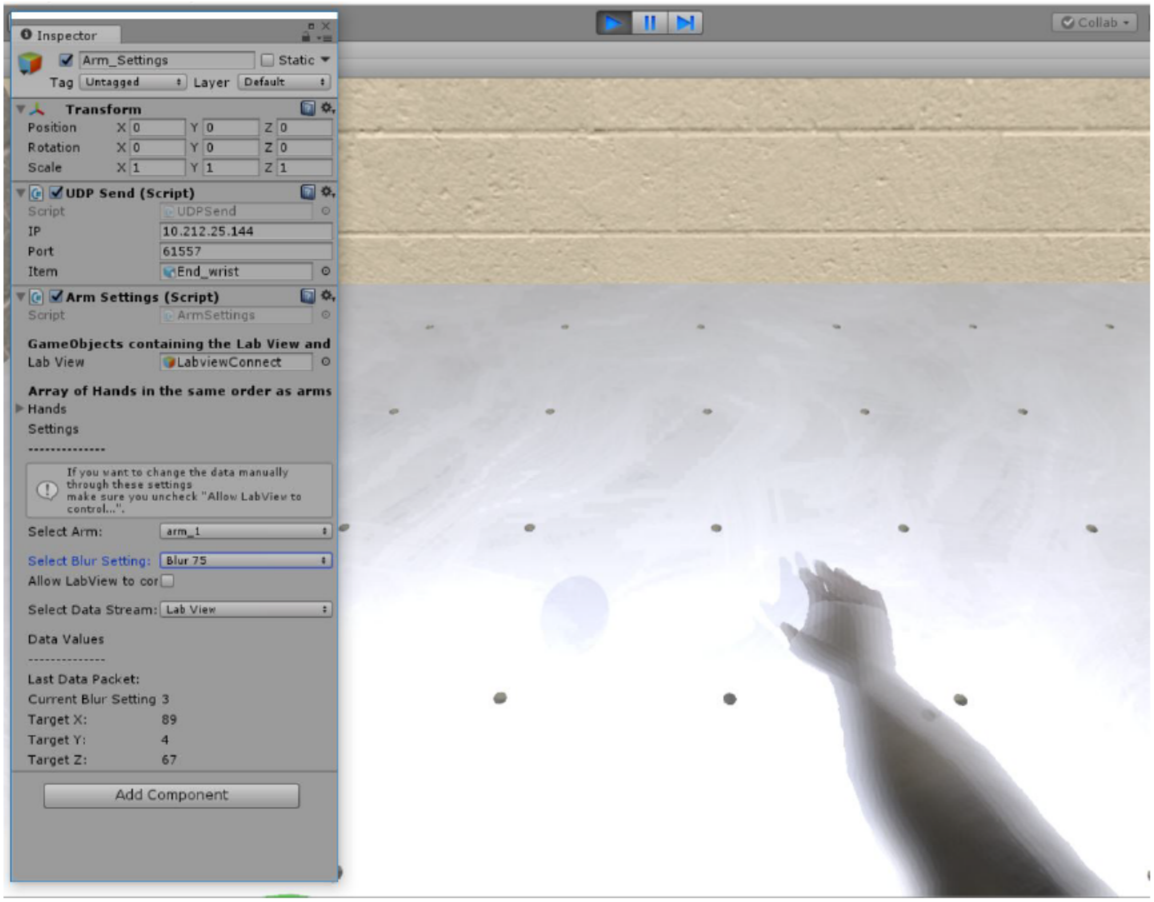

Figure 10. Rhesus macaque monkey avatar arm with 75% blurring.

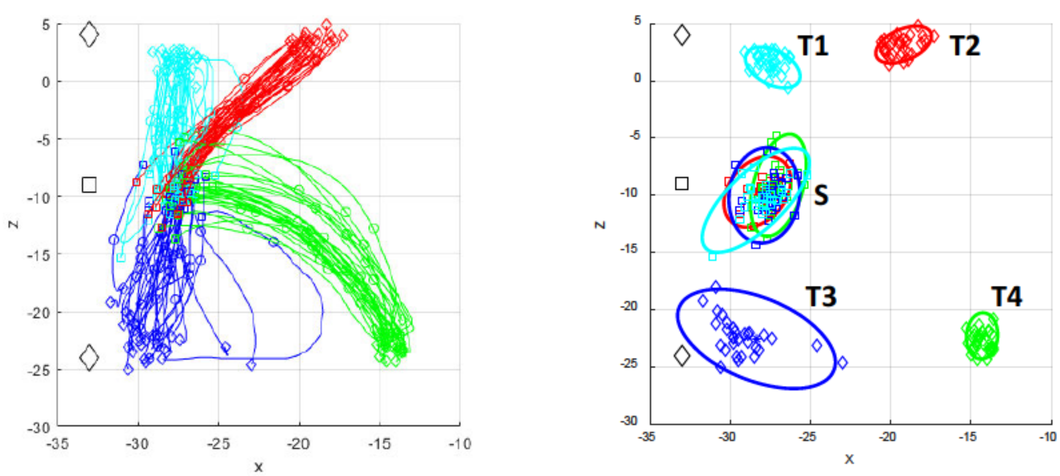

Figure 11. Left: Top down view of monkey handpaths generated from a single starting location (S) to four targets (T1-T4). Approximately 20-30 movements to each target are shown. Right: Variability in corresponding starting and endpoint positions, with 95% confidence ellipses superimposed.

Project Report Printer Friendly Version

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Preview of Award 1557886 - Annual Project Report

Cover | Accomplishments | Products | Participants/Organizations | Impacts | Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	**4900**
Federal Grant or Other Identifying Number Assigned by Agency:	**1557886**
Project Title:	**Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
PD/PI Name:	**Bijan Pesaran, Principal Investigator**
Recipient Organization:	**New York University**
Project/Grant Period:	**09/15/2016 - 08/31/2021**
Reporting Period:	**09/01/2018 - 08/31/2019**
Submitting Official (if other than PD\PI):	**Bijan Pesaran** **Principal Investigator**
Submission Date:	**10/09/2019**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Bijan Pesaran**

Back to the top

Accomplishments

*** What are the major goals of the project?**

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the

relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Our major activity this reporting period has been to extend the virtual reality environment and motion capture technology to enable binocular three-dimensional spatial percept and behavioral control. Commercially available systems are available for use in humans but there are no turnkey options for use in non-human primates. The challenge in doing this work is that monkeuys have smaller inter-ocular distance than humans. The turnkey systems for humans either use lenses that are either small and can be used with non-human but offer small fields of view or use large lenses that offer large fields of view but cannot be used in monkeys. Since the size of the field of view is know to constrain spatial perception in virtual reality, and since our goals involve studying perceptual processes, we elected to modify a system, specifically the Oculus Rift, and establish that it can be used to manipulate spatial perception as measured by eye movements in the awake behaving monkey.

Specific Objectives:

Develop a behavioral control and display system that combines our previous work on virtual reality displays (Putrino et al 2015) and eye tracking (Zimmermann et al 2018) for behavioral control in single system that provide binocular eye tracking in virtual reality for non-human primates with a large, greater than 70 degrees of visual angle, field of view.

Significant Results:

We have successfully reverse engineered the Oculus Rift to allow the lenses to be used at larger focal distance and so accomodate the smaller interocular distance of the macaque monkey. To correct for lensing distortions, we modeled the light path from the display through the lenses onto the retina for each eye in Zemax and corrected for the new positions of the optical elements. Calibration is confirmed by presenting a display consisting of vertical lines of different colors at different horizontal eccentricities and using a camera system positioned at the location of the monkeys retina to view the display. In doing so, we can introduce binocular eye tracking by positioning the TFT displays to the side of each eye, laterally in a wheatstone bridge configuration. We then use a hot mirror (ie infrared transparent mirror) to direct the images from the TFT displays to the eye and position an eye tracking camera in the straight-ahead position to measure eye position. Oculomatic is used to capture eye position, and software to control the display is implemented in Unity.

Key outcomes or Other achievements: We have successfully completed the binocular eye tracking and calibrated virtual reality and confirmed a monkey can successfully perform eye movements for juice rewards to different locations in the field of view using the system.

*** What opportunities for training and professional development has the project provided?**

A professional programmer (b) (6) [redacted] was interested in broadening his horizons by volunterring in the lab and working on this project. (b) (6) [redacted] has learned how to perform optical ray tracing in Zemax, technical programming to implement the integrated system and system integration skills to debug and correct for latency and jitter in the system. A post-graduate research technician (b) (6) [redacted] has been given opportunities in the development of this system to learn how to assess system performance and measure jitter and latency of the integrated visual and oculomotor tracking. (b) (6) [redacted] has also been trained in how to assess animal behavior specifically the spatial perception when working in the binocular virtual world.

*** How have the results been disseminated to communities of interest? If so, please provide details.**

The results will be presented at the upcoming Society for Neuroscience meeting but have not yet been disseminated.

*** What do you plan to do during the next reporting period to accomplish the goals?**

In the next reporting period we will extend our characterizations to three-dimensional binocular eye movements, ie vergence movements, as our current efforts have been limited to saccades to targets on a plane. We will publish a methods paper reporting the development and performance of this system. We will also support neurophysiological data analysis as the recordings become available.

[Back to the top](#)

Products

Books

Nothing to report.

Book Chapters

Nothing to report.

Inventions

Nothing to report.

Journals or Juried Conference Papers

Nothing to report.

Licenses

Nothing to report.

Other Conference Presentations / Papers

Nothing to report.

Other Products

Nothing to report.

Other Publications

Nothing to report.

Patent Applications

Nothing to report.

Technologies or Techniques

Nothing to report.

Thesis/Dissertations

Nothing to report.

Websites or Other Internet Sites

Nothing to report.

Back to the top

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
(b) (6) [redacted]	Other Professional	(b)(4), (b)(6) [redacted]
[redacted]	Technician	[redacted]
Pesaran, Bijan	PD/PI	[redacted]

Full details of individuals who have worked on the project:

(b) (6) [redacted]
Most Senior Project Role: Other Professional
Nearest Person Month Worked: (b)(4), (b)(6) [redacted]
Contribution to the Project: Development of software and algorithms for binocular virtual reality and eye tracking.
Funding Support: No funding requested
International Collaboration: No
International Travel: No

(b)(4), (b)(6) [redacted]
Most Senior Project Role: Technician
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Debugging and assessment of the binocular virtual reality and eye tracking system for non-human primates.
Funding Support: No funding requested
International Collaboration: No
International Travel: No

Bijan Pesaran
Email: bijan@nyu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 1
Contribution to the Project: Oversee work on project goals.
Funding Support: No funding requested
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Christopher Buneo	Academic Institution	Phoenix, Arizona

Full details of organizations that have been involved as partners:

Christopher Buneo
Organization Type: Academic Institution
Organization Location: Phoenix, Arizona
Partner's Contribution to the Project:
Collaborative Research
More Detail on Partner and Contribution:

What other collaborators or contacts have been involved?

Nothing to report

Back to the top

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The proposed research has significant potential to impact our understanding of basic neural processes such as multisensory integration, state estimation, and sensorimotor control while also advancing the fundamental engineering knowledge necessary to create the next generation of brain-machine interfaces (BMIs). Next generation BMIs for replacing lost limb function are envisioned to support the integration of artificial somatosensory feedback (tactile/proprioceptive) with natural vision (Bensmaia and Miller, 2014). The feasibility of such systems has already been established using monkey models (Shokur et al., 2013; Dadarlat et al., 2015). Optimizing these systems however will depend critically on understanding how natural visual and somatosensory signals interact within and among multisensory brain areas and their associated neural networks. Here we will address this knowledge gap by quantifying changes in spiking, local field potential (LFP) activity and neural coherence that result from integration of natural visual and somatosensory signals generated during arm movements. This will be performed in frontal and parietal brain areas of the monkey that have been implicated in sensorimotor control of the arm. The joint analysis of spiking and local field potential activity measured at different sites in the brain offers a unique opportunity to examine functional interactions between neurons and ensembles of neurons across large-scale brain networks. Spike-field coherence is a measure of association using these signals that links different scales: ~10-50um for spiking activity and ~200-500um for local field potential activity. This provides a bridge to less invasive measures of neural activity such as electrocorticography on the surface of the brain and EEG non-invasively at the scalp.

Optimizing multisensory BMIs will also require understanding how perceptual and action-related brain representations evolve as subjects learn to use and ultimately embody these devices. Current state-of-the-art robotic devices are not yet capable of the real-time, high-dimensional, natural movements that are likely necessary for embodiment (Putrino et al., 2015). Even if such devices were currently available, other factors would likely make them impractical for patients to use without extensive training. Virtual devices however offer a safe and practical alternative to robotic ones, allowing a multitude of behaviors to be learned and trained (Bohil et al., 2011; Putrino et al., 2015). Precisely how realistic such environments need to be to enable embodiment is unclear; diverse virtual stimuli have been used in different studies, with no attempt to determine the optimal (or minimal) stimulus for enabling embodiment. The studies proposed here, which involve virtual reaching tasks that vary the degree of reliability and semantic information about limb structure, will provide critical insights in this regard. This information will in turn advance the development of BMIs and related assistive technologies designed to improve the quality of life of individuals with sensorimotor disabilities.

What is the impact on other disciplines?

Nothing to report.

What is the impact on the development of human resources?

This project has contributed to human resource development by providing research and training opportunities for a volunteer and a technician in the integration and testing of hardware and software to perform binocular virtual reality experiments.

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

The display and behavioral control technology we have developed in this performance period will be of use to other researchers seeking to analyze and control behavioral mechanisms in three-dimensional environments.

What is the impact on society beyond science and technology?

Nothing to report.

Back to the top

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.
Back to the top

Project Report Printer Friendly Version

Click here to print

Preview of Award 1558151 - Annual Project Report

Cover | Accomplishments | Products | Participants/Organizations | Impacts | Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	**4900**
Federal Grant or Other Identifying Number Assigned by Agency:	**1558151**
Project Title:	**Collaborative Research: Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
PD/PI Name:	**Christopher A Buneo, Principal Investigator**
Recipient Organization:	**Arizona State University**
Project/Grant Period:	**09/15/2016 - 08/31/2021**
Reporting Period:	**09/01/2019 - 08/31/2020**
Submitting Official (if other than PD\PI):	**Christopher A Buneo Principal Investigator**
Submission Date:	**09/01/2020**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Christopher A Buneo**

Back to the top

Accomplishments

*** What are the major goals of the project?**

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations

interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities: Major activities included 1) Training of lab personnel, 2) Refinement of the virtual reality training platform used to accomplish all of the project's objectives, 3) Training of animals, 4) Behavioral analyses, 5) Surgical planning.

Specific Objectives:

1) Characterize the effect of varying semantic information about limb structure on oscillatory and spiking activity within multimodal cortical areas during arm state estimation

Cross-modal sensory stimuli are integrated not only for the formation of body schema, which is used for action, but also for the formation of the body image, which contributes to our sense of limb ownership. The latter in particular appears to be strongly influenced by semantic knowledge about how the body is structured. Here we will characterize the effects of varying such semantic knowledge on spiking, LFP activity, and local (areal) neural coherence across multimodal networks of the frontal and parietal lobes which display varying visual/somatic feedback sensitivities (PMv, area 5, and 7b). Monkeys will make reaching movements while receiving semantic information of varying complexity in different experimental blocks, ranging from an abstract arm endpoint stimulus (a sphere) to a fully rendered monkey avatar arm. Analysis will focus on a short, 1 second static holding period preceding reaching movements to virtual targets. We predict that as semantic information becomes more complex (i.e. more arm-like), reach reaction times will decrease and recording sites associated with representing the body image will show progressively larger effects of integration. More specifically, we predict that neural population responses, indexed by LFP power in the gamma band (which has been implicated in body-ownership) will be progressively enhanced and will be coherent with the spikes emitted by the cells that show enhanced spiking. Conversely, we predict that sites associated with representing the body schema will show minimal or no effects of semantic complexity. Instead, presentation of any visual stimulus will generally result in suppressed LFP power in the beta band (implicated in sensorimotor state) at these sites, which will be coherent with the spikes of cells that are suppressed. Lastly, sites involved in representing both body image and body schema are predicted to show evidence of cross frequency (beta-gamma) coupling. Changes in spiking and the direction of this change (enhancement/suppression) should reflect the strength of coupling at these sites.

2) Elucidate changes in oscillatory and spiking activity within multimodal cortical areas as a function of changes in the relative reliability of visual and somatic position cues

Psychophysical studies have demonstrated that sensory signals are optimally (or near optimally) integrated during both perceptual and action tasks in that they are weighted according to their relative reliabilities. Cortical correlates of optimal integration have been identified at the single cell and population levels during perceptual tasks but not during motor tasks and network level correlates of multimodal integration are poorly understood in general. As a result, in SA2 we will quantify changes in spiking, LFP activity, and local neural coherence in frontal and parietal areas as a function of the reliability of visual state (position) information. As in SA1 monkeys will make reaching movements to virtual targets and analysis will focus on the static holding period preceding the reach. Reliability of the visual information will be varied on a trial by trial basis by providing either a clear visual stimulus, one of two levels of a blurred visual stimulus, or no visual stimulus. We predict that as visual state information becomes more reliable, variability in limb positions will decrease and recording sites associated with representing the body schema will show progressively larger effects of integration. Specifically, we predict that LFP power in the beta band will be progressively suppressed and will be coherent with the spikes of cells that show suppressed spiking. Conversely, we predict that sites associated with representing the body image will show minimal or no effects of visual reliability. Instead, presentation of visual stimuli that recruited the body image in SA1 will generally result in enhanced LFP power in the gamma band, which will be coherent with the spikes of cells that are enhanced. Lastly, sites involved in representing both body image and body schema should again show evidence of cross frequency (beta-gamma) coupling and changes in spiking that reflect the strength of coupling.

3) Characterize changes in functional connectivity among multimodal cortical areas as a function of changes in semantic information and sensory reliability

For this aim, no new experiments will be conducted. Instead this aim will focus on quantifying the degree of functional connectivity among sites in multimodal parietal and frontal areas. That is, we predict that sites involved in body schema and/or body image will show strong evidence of functional connectivity, assessed via inter-areal (long-range) neural coherence. More specifically, sites involved in body image will change show progressively stronger correlations as semantic information increases and sites involved in representing the body schema will show progressively stronger correlations as visual state information increases. However we hypothesize that changes in functional connectivity will be stronger between sites with similar visual-somatic sensitivities. That is, increasing the reliability or semantic information of visual signals should be associated with stronger changes in correlations between sites in strongly-moderately visual areas (PMv and 7b) than between areas that are strongly-moderately somatosensory (area 5 and 7b).

Significant Results:

In the past year we have focused on refinements to our behavioral paradigm and analyses of our behavioral data. To review, the main software components of our behavioral control system are Cortex (the software interface for the Motion Analysis motion capture system), LabVIEW, and Unity 3D. Cortex records the marker positions and uses Calcium Solver, a built in skeletal engine, to generate a segment model which is streamed to Unity to animate avatars. LabVIEW controls the sequence of events on a given trial, including sending the coordinates of reach targets to Unity for rendering. Unity, in addition to rendering the avatar, targets, and other components of the VR environment, sends the current position of the endpoint of the arm to LabVIEW to allow for checking of arm position against target position, allowing the task to proceed and for behavioral reinforcement to occur. This system architecture is illustrated in the supporting documentation, Figure 4.

In the past year, we have made two major refinements to this system. The first was the addition of motion tracking of the wrist and fingers. In the beginning, in order to expedite training we began tracking the arm with only 3 markers (shoulder, elbow, wrist), which worked well in the sense that we were able to reliably track and control each animal's behavior. However, since one of the main objectives of the project is to probe body image (or more precisely, body ownership) it is imperative that the animals believe (to the greatest extent possible) that the image of an arm that they are viewing is in fact their own arm. Without seeing motion of the fingers and wrist this is not possible. Thus, we added additional markers to the wrist and fingers in order to render this motion in VR. This is not trivial as it requires not only getting the animals accustomed to wearing the additional markers but also involves generating new segment models to animate the avatars. The second refinement to our system was the addition of eye tracking. This was planned from the outset but only implemented recently. Importantly, we did this in collaboration with Bijan Pesarans's lab (a collaborator on the project) who had previously developed a high-speed, open source, low cost eye tracking system for use with humans and non-human primates. With the Pesaran lab's help we were able to acquire and build the hardware and software components necessary to track the eyes in our system.

Regarding behavioral analyses, we have now quantified the effects of vision and tactile feedback on arm movement planning in our environment. One of our initial predictions was that altering the reliability of the visual information about arm position will alter the relative weighting of vision and somatosensation, changing both the neural responses in areas associated with the representation of arm position and as well as the behavior of the animals. Behavioral changes that would be expected include alterations in the variability of initial movement directions and/or movement endpoints. As a result we have developed methods to quantify behavioral variability and have now analyzed the initial and final directional variability in both animals using kinematic data obtained over 10 days. Critically, we have found effects of both visual and tactile feedback on initial and final movement directions. This will greatly aid in the interpretation of any changes in neural responses induced by our manipulations of visual and tactile feedback. Summary figures showing the results of these analyses can be found in the supporting documentation, Figures 5-8; Table I.

Key outcomes or Other achievements:	1) We have refined the behavioral environment in which the animals interact as described above to allow for tracking of finger, wrist, and eye motion. 2) We have presented a paper describing our experimental paradigm at the 2020 IEEE Engineering in Medicine and Biology Society Conference (EMBC) and received very positive feedback regarding that paper. For example, one review commented “This is a fascinating instance of modular BMI design for VR limb representation” and a second reviewer added “This paper is very interesting and the experiment was well-designed and performed”. 3) We have analyzed the kinematic data of two animals and have verified that our manipulations of visual and tactile feedback are having the desired effect on movement variability.

*** What opportunities for training and professional development has the project provided?**

During the last project period the project has enhanced the mentoring of 1 Research Scientist, 1 PhD student (female), 1 lab manager/animal technician (female), and 2 undergraduate students (1 female, 1 African American male).

*** How have the results been disseminated to communities of interest? If so, please provide details.**

To date, the results have been disseminated through a peer-reviewed conference proceeding and presentation at EMBC 2020. The results have also been disseminated by the PI to undergraduate and graduate students in biomedical engineering and neuroscience at Arizona State University through relevant courses in physiology, biomedical engineering, and neuroscience.

*** What do you plan to do during the next reporting period to accomplish the goals?**

During the next reporting period we plan to do the following:

1) Complete initial behavioral analyses in both animals and submit the results for publication.

2) Explore the effects of manipulations of semantic information on the reaching behavior in both animals.

2) Implant both animals with microelectrode recording arrays and begin charaterizing the effect of manipulations of visual (semantic information, reliabilty) and tactile feedback on neural responses in parietal and premotor cortex.

3) To enhance Broader Impacts, recruit additional undergraduate and Master's level students to be involved in the project and encourage all students and staff to participate in seminars and colloquia addressing the ethical, societal, and policy implications of neuroscience research. Also, increase dissemination of the results of the project through seminars and other public venues.

Supporting Files

	Filename	Description	Uploaded By	Uploaded On
(Download)	Supporting_Documentation.pdf	File illustrating some of the significant results of the project.	Christopher Buneo	09/01/2020

Back to the top

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

Phataraphruk, P., Van Gilder, P. Buneo, C.A. (2020). Virtual reality platform for systematic investigation of multisensory integration and training of closed-loop prosthetic control.. *Conf Proc IEEE Eng Med Biol Soc.*. 2020 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

(b)(4), (b)(6) [redacted]. . Status = OTHER; Acknowledgment of Federal Support = Yes ; Peer Reviewed = No

Van Gilder, P. Shi, Y. Apker, G.A. Buneo, C.A. (2020). Sensory feedback-dependent coding of arm position in local field potentials of the posterior parietal cortex. *Scientific Reports*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses

Other Conference Presentations / Papers

Preyaporn Phataraphruk Qasim Rahman Kishor Lakshmi Narayanan Mitchell Fruchtman Christopher Buneo (2019). *Effects of initial arm posture on reach endpoint variability.*. Annual Meeting of the Society for Neuroscience. Chicago. Status = ACCEPTED; Acknowledgement of Federal Support = Yes

Amanda Knight Preyaporn Phataraphruk (2019). *Optimizing Success in NHP work with Individualized Problem Solving Strategies*. Annual Meeting of The American Association for Laboratory Animal Science. Denver. Status

= ACCEPTED; Acknowledgement of Federal Support = Yes

Other Products

Other Publications

Patent Applications

Technologies or Techniques

This project has led directly to the development of a novel virtual reality platform for systematic investigation of multisensory integration and training of closed-loop prosthetic control. The main software components of this system are Cortex (the software interface for the Motion Analysis motion capture system), LabVIEW, and Unity 3D. Cortex records the marker positions and uses Calcium Solver, a built in skeletal engine, to generate a segment model which is streamed to Unity to animate a custom avatar (created in Maya). Labview controls the sequence of events on a given trial, including sending the coordinates of reach targets to Unity for rendering. Unity, in addition to rendering the avatar, targets, and other components of the VR environment, sends the current position of the endpoint of the arm to Labview to allow for checking of arm position against target position, allowing the task to proceed and for behavioral reinforcement to occur. A full description of the system can be found in:
Phataraphruk, P., Van Gilder, P., Buneo, C.A. Virtual reality platform for systematic investigation of multisensory integration and training of closed-loop prosthetic control. *Conf Proc IEEE Eng Med Biol Soc. 2020*; 1-4, 2020.

Thesis/Dissertations

Websites or Other Internet Sites

Supporting Files

	Filename	Description	Uploaded By	Uploaded On
(Download)	Phataraphruk EMBS 2020 final.pdf	Peer-reviewed conference paper describing the behavioral control system.	Christopher Buneo	08/31/2020

Back to the top

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Buneo, Christopher	PD/PI	[redacted]
Knight, Amanda	Technician	[redacted]
VanGilder, Paul	Staff Scientist (doctoral level)	[redacted]
Phatarphruk, Preyaporn	Graduate Student (research assistant)	[redacted]
[redacted]	Undergraduate Student	[redacted]
[redacted]	Undergraduate Student	[redacted]

Full details of individuals who have worked on the project:

Christopher A Buneo
Email: christopher.buneo@asu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked [redacted]
Contribution to the Project: Administered the project, trained the PhD student (Phataraphruk) and research scientist (VanGilder), and participated in data analysis and writing of papers
Funding Support: [redacted]
International Collaboration: No
International Travel: No

Amanda Knight
Email: arknigh2@mainex1.asu.edu
Most Senior Project Role: Tech
Nearest Person Month Worked [redacted]
Contribution to the Project: Provided veterinary care to the animals; trained animals; trained graduate and undergraduate students.
Funding Support: [redacted]
International Collaboration: No
International Travel: No

Paul VanGilder
Email: pvangild@asu.edu
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: [redacted]
Contribution to the Project: Cod[redacted]m; installed of eye tracking system; mentoring of PhD and undergraduate students, training of animals, data analysis and writing of papers.
Funding Support: [redacted]
International Collaboration: No
International Travel: No

Preyaporn Phatarphruk
Email: pphatara@asu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: [redacted]
Contribution to the Project: Trained animals; trained technician and undergraduate student in setup of motion capture system and LabVIEW behavioral control programs; developed behavioral control system; participated in data analysis, writing of papers, and conference presentations.
Funding Support: None.
International Collaboration: No
International Travel: No

[redacted]
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: [redacted]

Contribution to the Project: Training of animals; providing assistance to vet tech/lab manager and graduate student.
Funding Support: None.
International Collaboration: No
International Travel: No

(b) (6) [redacted]

Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Training of animals; providing assistance to vet tech/lab manager and graduate student.
Funding Support: (b)(4), (b)(6) [redacted]
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
New York University	Academic Institution	New York City

Full details of organizations that have been involved as partners:

New York University
Organization Type: Academic Institution
Organization Location: New York City
Partner's Contribution to the Project:
In-Kind Support
Collaborative Research
More Detail on Partner and Contribution: New York University is the home institution of B jan Pesaran, the co-PI/PD on the project.

What other collaborators or contacts have been involved?

(b) (4) [redacted].

Back to the top

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Next generation BMIs for replacing lost limb function are envisioned to support the integration of artificial somatosensory feedback (tactile/proprioceptive) with natural vision. Optimizing these systems will depend critically on understanding how natural visual and somatosensory signals interact within and among multisensory brain areas and their associated neural networks. Precisely how realistic such environments need to be to enable embodiment is unclear; diverse virtual stimuli have been used in different studies, with no attempt to determine the optimal (or minimal) stimulus for enabling embodiment.

During the last reported period we began analyzing the behaviors of two non-human primates engaged in virtual reaching tasks that vary the degree of reliability limb position. To date we have found effects of both visual and tactile feedback on initial and final movement directions. These findings will greatly aid in the interpretation of associated changes in neural responses induced by our manipulations of visual (semantic and reliability) and tactile feedback. This information will in turn advance the development of BMIs and related assistive technologies designed to improve the quality of life of individuals with sensorimotor disabilities.

What is the impact on other disciplines?

The VR system developed here for non-human primates can easily be duplicated for use in studies of human sensorimotor control and perception, including in the PI's own human motor control lab at Arizona State University.

What is the impact on the development of human resources?

During the last period the project provided research and training opportunities for one research scientist, one PhD student, one technician/laboratory manager and two undergraduate student. Both undergraduate students are from traditionally underrepresented groups. All students have been exposed to animal training and handling and well as motion capture and virtual reality techniques. In addition, the PhD student has received additional training in basic surgical techniques.

These experiences and those to come will provide students and staff associated with the project greater access to career-related and other opportunities in research, teaching, or health care.

What is the impact on physical resources that form infrastructure?

The project has led to the rebuilding of the PI's non-human primate laboratory at Arizona State University. This facility is designed for the acquiring and analyzing behavioral and neural data in non-human primates and is available for use by the PI and his collaborators at ASU.

What is the impact on institutional resources that form infrastructure?

None.

What is the impact on information resources that form infrastructure?

None.

What is the impact on technology transfer?

None.

What is the impact on society beyond science and technology?

None.

Back to the top

Changes/Problems

Changes in approach and reason for change

Assessing the effects of tactile/haptic cues on the behavioral and neural responses is a new addition to the approach. We initially started using such cues to allow the animals to more easily localize targets in the VR environment during training. Later however we realized that animals were able to perform the task with and without such cues, which presented an opportunity to assess the effects of tactile and haptic feedback on reaching behavior and neural activity. This will enhance the overall impact of the project.

Actual or Anticipated problems or delays and actions or plans to resolve them

The response of our institution (ASU) to the COVID-19 pandemic has unfortunately caused delays in progress on the project. During the early part of 2020 (prior to the pandemic) we were finalizing training of the animals and engaged in the planning of implant surgeries for both animals. However, part of ASU's response to the pandemic was a partial shutdown of all 'non-essential' activities, which impacted some research activities. We were fortunate in the sense that we did not have to completely discontinue work in my non-human primate lab (though my human facilities were completely shut down) however due to the fact that 1) the reseach scientist had a pre-existing condition that put him at greater risk for infection and 2) the laboratory technician had pandemic related impacts on her childcare, work on campus for these individual was intermittent. In addition, when any students/staff were on campus they were required to be on staggered schedules which precluded cooperation on tasks which required more than one person (such as integrating the eye tracker into the system).

Thus, the COVID-19 pandemic led to postponement of implant surgeries, delays in acquiring additional behavioral data for analysis and eventual publication, postponement of conference abstract submission and presentation due to cancellation of scientific meetings (such as the Society for Neuroscience annual meeting) among other disruptions. During this time we focused on refinements to our behavioral control system and extensive analyses of our behavioral data.

This month (August 2020) we were given approval to resume research activities, with certain safeguards in place regarding disinfection of equipment and surfaces, social distancing, etc. This is in addition to ASU's own procedures for students and staff which include daily health checks. We are now working on getting animals back up to speed on their tasks and planning implant surgeries for later this fall.

Assuming that COVID-19 cases do not spike, I do not anticipate further major delays in progress.

Changes that have a significant impact on expenditures

Delays in progress caused by the COVID-19 pandemic may have an impact on expenditures. More specifically, I was expecting to have enough funds to be able to request a no-cost extension of the project after year 5 and continue data analyses etc. This may or may not be possible without finding another source of funding for the students or staff.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.

Back to the top

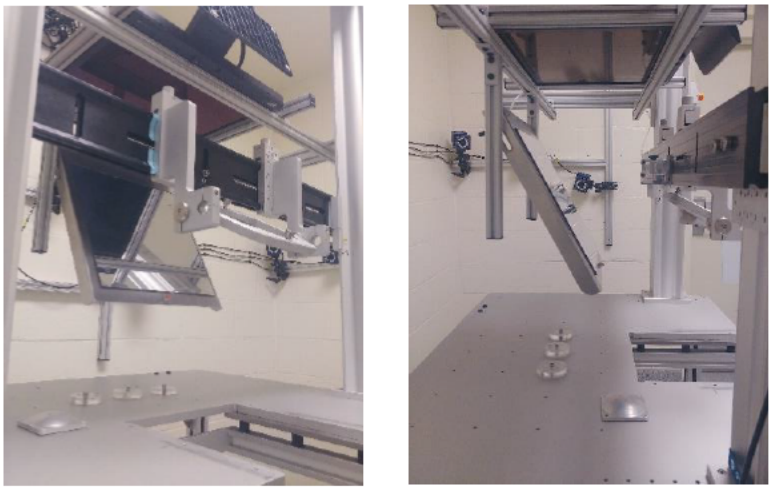

Figure 1. Oblique (A) and side (B) views of the tabletop and projection system, including the display mirror. Animal's chair is positioned at the cutout in the table and the animal initially positions their hand at one of three locations on the tabletop, indicated by the circular plastic discs. The VR environment is displayed on a 3D monitor (oriented horizontally above the tabletop) and projected onto the mirror in front of the animal.

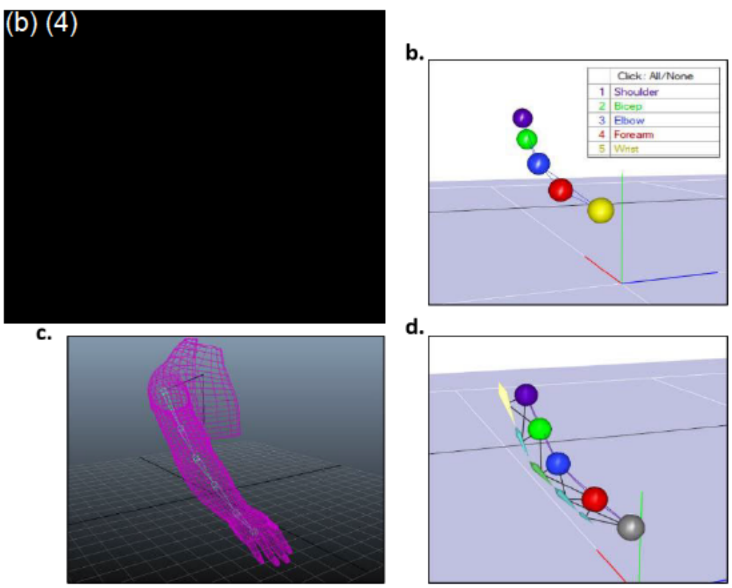

Figure 2. Process for driving avatar animation with kinematic data. (a) Motion capture sleeve attached to animal's right arm. This is a typical pose taken for the static capture. (b) Completed marker set with color coded markers connected by links. (c) Avatar model mesh. (d) Segment model contains bones attached (black lines) to the markers in the Model Pose. Bones pulled out for visualization but are normally embedded into the markers.

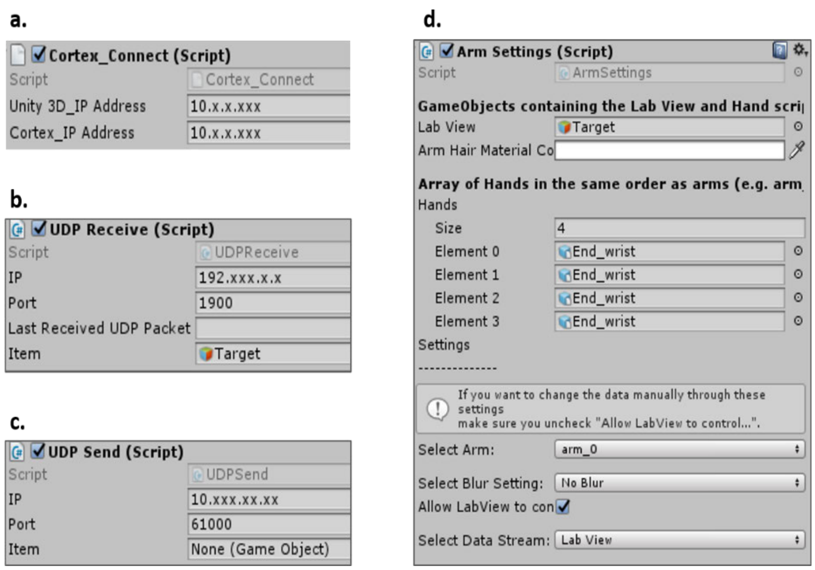

Figure 3. Unity3D game interface showing scripts that communicate to other programs in the setup. (a) Cortex Connect script specifying IP addresses for the workstations. (b) UDP Receive script specifying the connection protocols necessary for LabVIEW to control the specified Item (Target) in Unity3D. (c) UDP Send script specifying the connection protocol for communication from Unity3D to LabVIEW. The Item parameter is automatically updated to the hand of the selected arm. (d) Arm Settings script for selection of avatar arms and their visual properties. “Arm Hair Material Color” is a hex color code specifying the blurring effect. “Hands” is an array containing all the bones associated to the hand of each avatar.

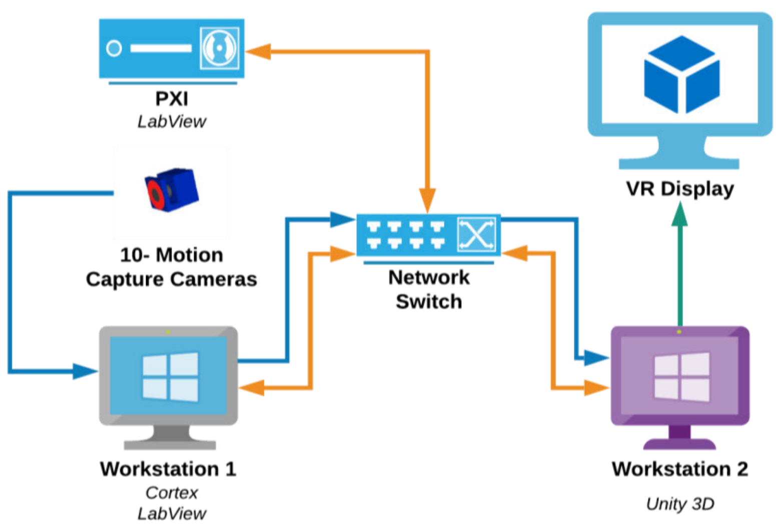

Figure 4. System architecture. Blue Arrows: motion capture data from cameras is sent to Workstation 1 for processing in Cortex and then outputs to Workstation 2 to drive the avatar arm in Unity3D. Orange Arrows: data sent and received from LabVIEW. Green Arrow: display data to 3D monitor.

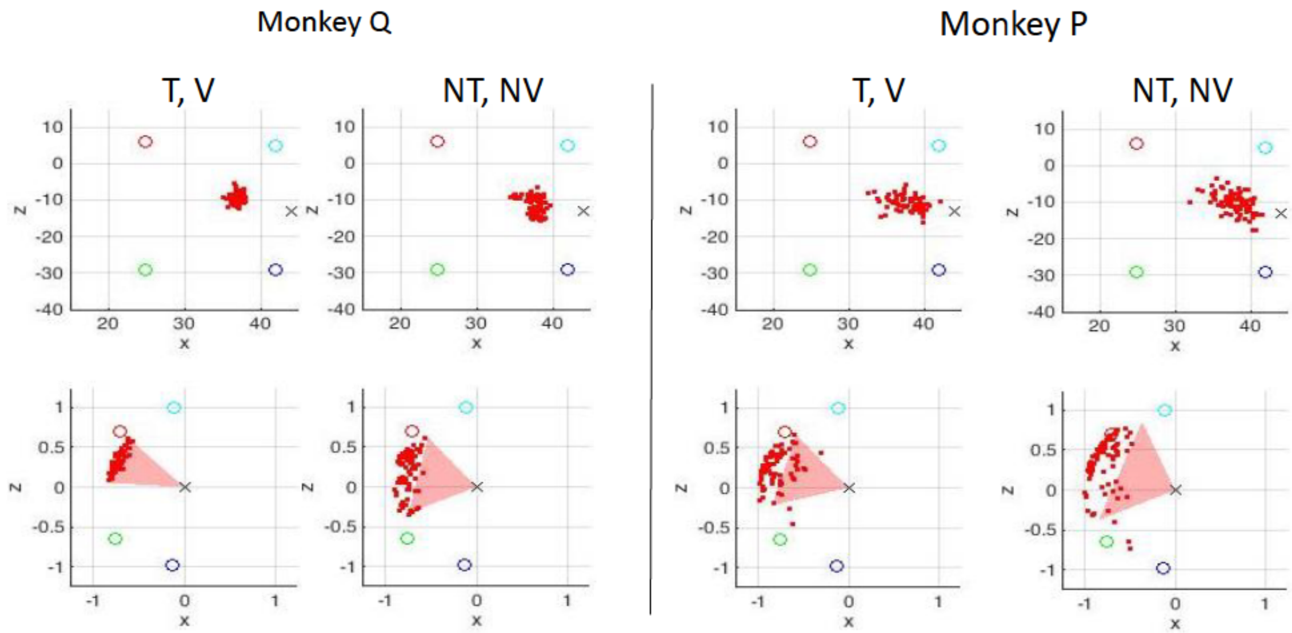

Figure 5. Condition-dependent differences in directional variability. Top: hand positions at 25% of the total movement for reaches directed from the start position (X) to Target 1 (red circle). T,V: trials with tactile and visual feedback at the starting position. NT,NV: trials without tactile and visual feedback. Bottom plots: positions normalized by movement extent, in order to visualize components of variability related only to direction. Although Monkey P was more variable overall, both animals exhibited markedly greater variability for movements initiated without visual or tactile feedback at the starting position.

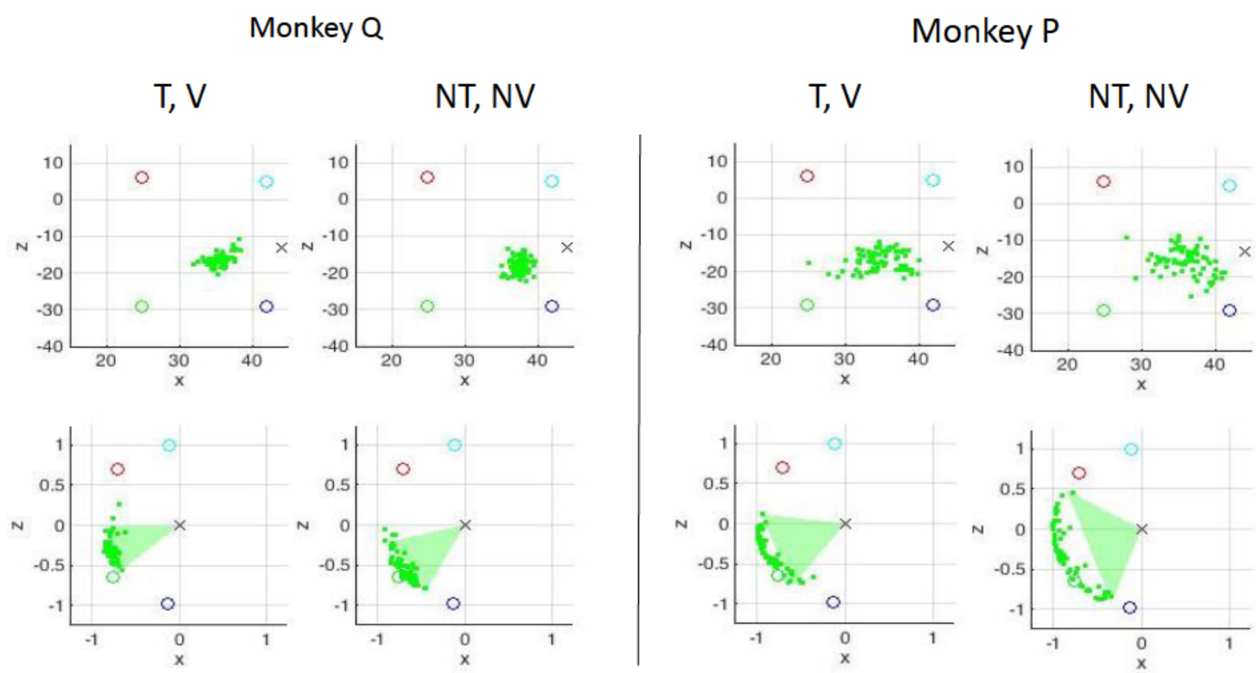

Figure 6. Condition-dependent variability for movements directed to Target 2 (green circle). Figure conventions as described in Fig. 5.

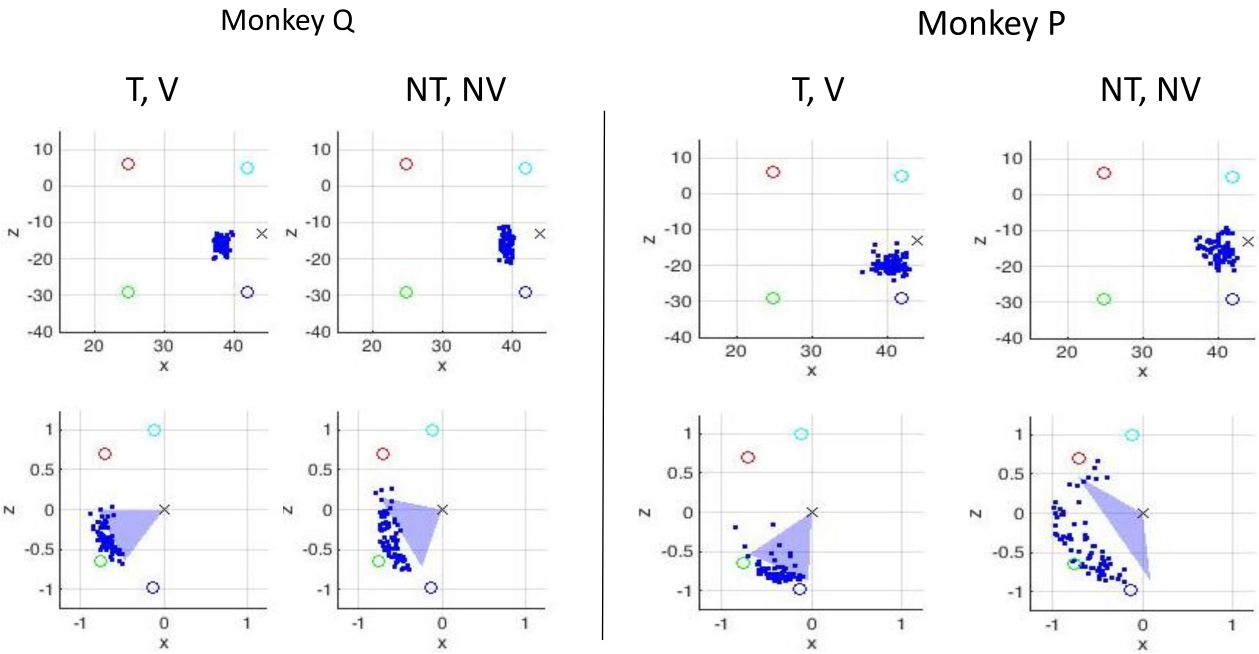

Figure 7. Figure 6. Condition-dependent variability for movements directed to Target 3 (blue circle). Figure conventions as described in Fig. 5.

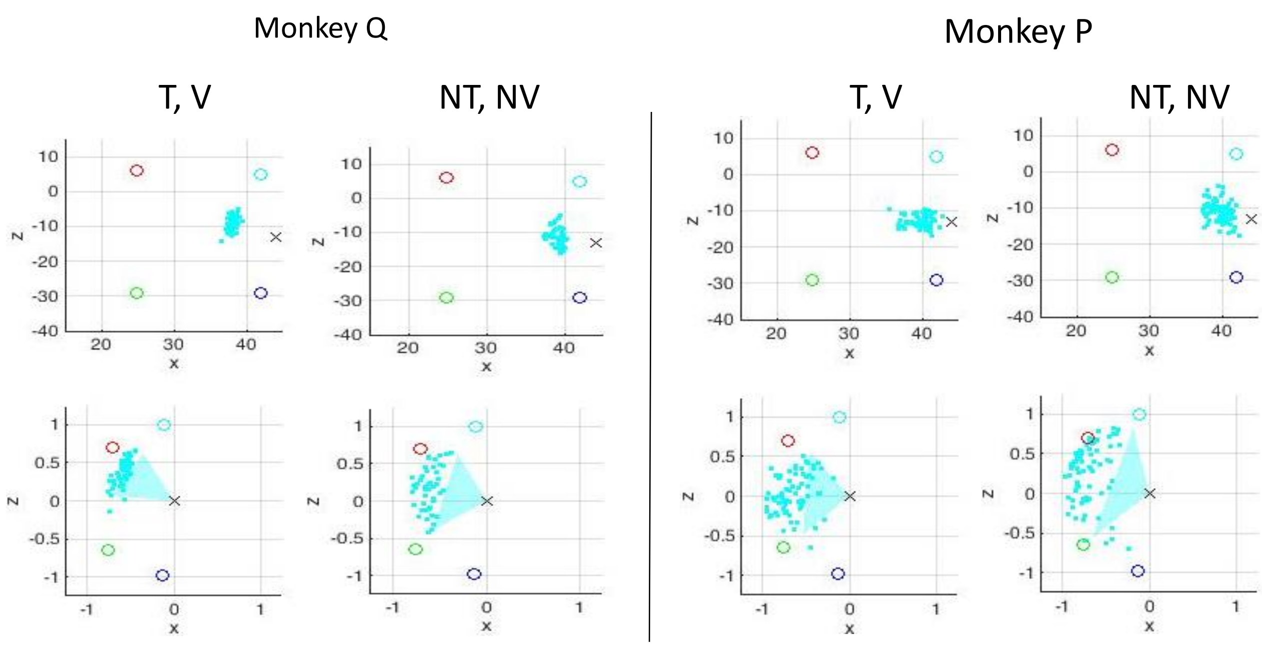

Figure 8. Figure 6. Condition-dependent variability for movements directed to Target 4 (cyan circle). Figure conventions as described in Fig. 5.

		Monkey Q					Monkey P		
	Target 1	Target 2	Target 3	Target 4		Target 1	Target 2	Target 3	Target 4
Circular mean (°), V+T:	155.6305	-159.28	-152.586	147.1049		162.9059	-157.198	-117.292	175.7091
Circular mean (°), NV+NT:	167.2189	-142.489	-150.197	165.1821		158.6534	-159.926	-148.497	161.5008
	Target 1	Target 2	Target 3	Target 4		Target 1	Target 2	Target 3	Target 4
Circular SD (°), V+T:	10.3079	9.6405	13.1021	13.5389		15.6615	14.7621	12.4432	22.7355
Circular SD (°), NV+NT:	18.0525	11.9906	20.4691	24.008		22.2663	24.326	31.0553	28.5781

Table I. Comparisons of circular means and standard deviations for conditions with and without visual and tactile feedback at the starting position. Values highlighted in gray differed significantly between conditions.

Project Report Printer Friendly Version

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Preview of Award 1557886 - Annual Project Report

Cover | Accomplishments | Products | Participants/Organizations | Impacts | Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	**4900**
Federal Grant or Other Identifying Number Assigned by Agency:	**1557886**
Project Title:	**Multimodal State Estimation through Neural Coherence in the Parieto-Frontal Network**
PD/PI Name:	**Bijan Pesaran, Principal Investigator**
Recipient Organization:	**New York University**
Project/Grant Period:	**09/15/2016 - 08/31/2021**
Reporting Period:	**09/01/2019 - 08/31/2020**
Submitting Official (if other than PD\PI):	**Bijan Pesaran** **Principal Investigator**
Submission Date:	**08/27/2020**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Bijan Pesaran**

Back to the top

Accomplishments

*** What are the major goals of the project?**

Estimating the state of the body through the integration of available sensory cues (multimodal state estimation) is a critical integrative function for most organisms. Although much is known about state estimation for the upper limb at the behavioral level, underlying neural mechanisms remain poorly understood in cortical areas, particularly at the network level. This is due to several factors: 1) the cortical areas believed to play a role in limb state estimation are heterogenous with regard to the relative strength of their sensory inputs and have shown evidence of both multisensory enhancement and suppression depending on context; 2) functional interactions among these areas have yet to be characterized; 3) the

relation between sensitivity to visual and somatic cues and prevailing computational theories of multisensory integration have been incompletely explored; 4) multimodal areas are thought to contribute to both perceptual and action-based body representations but how these representations interact at the neural and behavioral levels is not well understood. As a result, it is unclear how a coherent multimodal estimate of the state of upper limb is constructed and maintained. Here we will address these knowledge gaps by quantifying changes in spiking, population responses measure by LFP activity and neural coherence within and between cortical areas of the monkey that have been implicated in limb state estimation. This will be facilitated during reaching tasks that alter the reliability and semantic information of visual cues by using a virtual environment.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:	Our major activity this reporting period centers on developing the closed-loop behavioral-electrophysiological task control interface needed to study neuronal mechanisms of spatial perception in an immersive virtual reality environment.
Specific Objectives:	Our specific objectives have been to update the behavioral task control interface to support the immersive virtual reality environment involving binocular three-dimensional spatial perception, to assess validity of the elicited spatial percepts using eye movements, and to integrate synchronized electrophysiological data acquisition for the large-scale neuronal recording and related closed-loop experiments necessary for this project.
Significant Results:	We have successfully implemented the behavioral task control interface in Unity to work with the immersive virtual reality environment based on the Oculus Rift that we developed in the previous reporting intervals. We have confirmed reliable behavioral control involving spatial perception in immersive virtual reality. We have done so by assessing the spatial accuracy of eye movements made to sensory objects presented at defined locations in the virtual environment. We have also integrated electrophysiological data acqusition hardware and software in a closed-loop platform that synchronizes data for feedback in real-time using the Robot Operating System framework to enable distributed computing. The electrophysiological data acquisition is compatible with Blackrock Microsystems, Intan hardware, Labview hardware and the recently developed Neuropixel hardware.
Key outcomes or Other achievements:	We have updated behavioral control and electrophysiogical software to support the immersive virtual reality environment developed in previous reporting intervals, and confirmed satisfactory performance.

*** What opportunities for training and professional development has the project provided?**

An lab technician [redacted] has worked on the project to develop and test software that updates the task control and data acqusition interface to use the immersive virtual environment previously developed in the lab [redacted] as learned how to debug instrument control software in C++, Python and Matlab and to perform real-time system integration necessary to validate performance.

*** How have the results been disseminated to communities of interest? If so, please provide details.**

We have not disseminated the work outside of our collaborative arrangement as part of this project.

*** What do you plan to do during the next reporting period to accomplish the goals?**

In the final reporting period, we will prepare a manuscript reporting the performance and design of the immersive virtual reality system, the electrophysiological data acqusition and behavioral control interface. We will prepare software for dissemination, and we will share the software on a github repository. We will also support neurophysiological data analysis as the recordings become available.

Back to the top

Products

Books

Nothing to report.

Book Chapters

Nothing to report.

Inventions

Nothing to report.

Journals or Juried Conference Papers

Nothing to report.

Licenses

Nothing to report.

Other Conference Presentations / Papers

Nothing to report.

Other Products

Nothing to report.

Other Publications

Nothing to report.

Patent Applications

Nothing to report.

Technologies or Techniques

Nothing to report.

Thesis/Dissertations

Nothing to report.

Websites or Other Internet Sites

Nothing to report.

Back to the top

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Pesaran, Bijan	PD/PI	(b) (4), (b) (6) [redacted]

(b)(4), (b)(6) [redacted]	Technician	(b)(4), (b)(6) [redacted]	

Full details of individuals who have worked on the project:

Bijan Pesaran
Email: bijan@nyu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: (b)(4), (b)(6) [redacted]
Contribution to the Project: Co-Investigator
Funding Support: (b)(4), (b)(6) [redacted]
International Collaboration: No
International Travel: No

(b)(4), (b)(6) [redacted]
Most Senior Project Role: Technician
Nearest Person Month Worked (b)(4), (b)(6) [redacted]
Contribution to the Project: Develop and test software that updates the task control and data acquisition interface
Funding Support: None
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Christopher Buneo	Academic Institution	Phoenix, Arizona

Full details of organizations that have been involved as partners:

Christopher Buneo
Organization Type: Academic Institution
Organization Location: Phoenix, Arizona
Partner's Contribution to the Project:
Collaborative Research
More Detail on Partner and Contribution:

What other collaborators or contacts have been involved?

Nothing to report

Back to the top

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The proposed research has significant potential to impact our understanding of basic neural processes such as multisensory integration, state estimation, and sensorimotor control while also advancing the fundamental engineering knowledge necessary to create the next generation of brain-machine interfaces (BMIs). Next generation BMIs for replacing lost limb function are envisioned to support the integration of artificial somatosensory feedback (tactile/proprioceptive) with natural vision (Bensmaia and Miller, 2014). The feasibility of such systems has already been established using monkey models (Shokur et al., 2013; Dadarlat et al., 2015). Optimizing these systems however will depend critically on understanding how natural visual and somatosensory signals interact within and among multisensory brain areas and their associated neural networks. Here we will address this knowledge gap by quantifying changes in spiking, local field potential (LFP) activity and neural coherence that result from integration of natural visual and somatosensory signals generated during arm movements. This will be performed in frontal and parietal brain areas of the monkey that have been implicated in sensorimotor control of the arm. The joint analysis of spiking and local field potential activity measured at different sites in the brain offers a unique opportunity to examine functional interactions between neurons and ensembles of neurons across large-scale brain networks. Spike-field coherence is a measure of association using these signals that links different scales: ~10-50um for spiking activity and ~200-500um for local field potential activity. This provides a bridge to less invasive measures of neural activity such as electrocorticography on the surface of the brain and EEG non-invasively at the scalp.

Optimizing multisensory BMIs will also require understanding how perceptual and action-related brain representations evolve as subjects learn to use and ultimately embody these devices. Current state-of-the-art robotic devices are not yet capable of the real-time, high-dimensional, natural movements that are likely necessary for embodiment (Putrino et al., 2015). Even if such devices were currently available, other factors would likely make them impractical for patients to use without extensive training. Virtual devices however offer a safe and practical alternative to robotic ones, allowing a multitude of behaviors to be learned and trained (Bohil et al., 2011; Putrino et al., 2015). Precisely how realistic such environments need to be to enable embodiment is unclear; diverse virtual stimuli have been used in different studies, with no attempt to determine the optimal (or minimal) stimulus for enabling embodiment. The studies proposed here, which involve virtual reaching tasks that vary the degree of reliability and semantic information about limb structure, will provide critical insights in this regard. This information will in turn advance the development of BMIs and related assistive technologies designed to improve the quality of life of individuals with sensorimotor disabilities.

What is the impact on other disciplines?

Nothing to report.

What is the impact on the development of human resources?

This project has contributed to human resource development by providing research and training opportunities for a volunteer and a technician in the integration and testing of hardware and software to perform immersive virtual reality and neurophysiological recording experiments.

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

The behavioral control and electrophysiological data acquisition software we have developed in this performance period will be of use to other researchers seeking to analyze neural and behavioral mechanisms in three-dimensional environments.

What is the impact on society beyond science and technology?

Nothing to report.
Back to the top

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.
Back to the top