



AFRL-AFOSR-VA-TR-2022-0399

Development of a Remote-fNIRS Device for use Under Naturalistic Working Conditions

**Hirshfield, Leanne
SYRACUSE UNIVERSITY
900 S CROUSE AVE STE 620
SYRACUSE, NY, 13244
USA**

**07/18/2022
Final Technical Report**

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Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203				10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR RTA2	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-VA-TR-2022-0399			
12. DISTRIBUTION/AVAILABILITY STATEMENT A Distribution Unlimited: PB Public Release								
13. SUPPLEMENTARY NOTES								
14. ABSTRACT Recent advancements in biotechnology have resulted in brain measurement devices that can noninvasively measure the functioning brain in people's natural environments. Functional NearInfrared Spectroscopy (fNIRS) is such a technique, which measures the hemoglobin signatures related to neural activation. With the potential to monitor people's mental states non-invasively and in real-time, researchers have used fNIRS devices to measure a myriad of cognitive and emotional states in operational settings [1-5]. Leading biotechnologists have created wireless implementations (Fig 1) of fNIRS for real-time brain monitoring under normal working conditions [6]. The device works by pulsing near-infrared light into the head, and using powerful light detectors to measure the light that is reflected back out of the head. The fNIRS is unique in its potential to take these measurements from a distance, without requiring contact with the head. While fNIRS implementations for measuring brain function have used source and detection fibers which are placed on the head of subjects directly, we have demonstrated that it is possible to modify this technology so that measurement of brain function can be done at a distance from the users								
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19a. NAME OF RESPONSIBLE PERSON LAURA STECKMAN					19b. PHONE NUMBER (Include area code) 426-7556			

Q469.



AFOSR Research Performance Progress

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You have reached AFOSR's report submission page. We have constructed this submission site to provide directions as you move through each page. Please contact technicalreports@us.af.mil if you have any questions or technical issues with the report.

After inputting your project's initial award information you will be able to use the Return to Main Menu button at the bottom of each page to navigate back and forth during your response. Thank you in advance for your patience in submitting this information, this information is of critical importance to our mission at AFOSR: To discover, shape and champion basic science research.

Q459.

Award Information

Q1. Award Number (Federal Award Identification Number XXXXXX-XX-X-XXXX)

FA9550-18-1-0074

Q2. Our records show that you have a: due. Please confirm by selecting the report type below.

Q3. Report Type

- ☒ Final Performance
- ☐ Interim (Annual) Performance
- ☐ Equipment Report
- ☐ Conference Summary

Q4. Principal Investigator

Mark R. Costa

Q5. Principal Investigator Email

mrcosta@syr.edu

Q7. Project Title

Development of a Remote-fNIRS Device for use Under Naturalistic Working Conditions

Q8. Recipient Organization

Syracuse University

Q310. Business Office Email

rgullo@syr.edu

Q9. Report Due Date (mm/dd/yyyy)

04/15/2022

Q10. Report Period Start Date (mm/dd/yyyy)

01/16/2018

Q11. Report Period End Date (mm/dd/yyyy)

01/15/2022

Q297. Current Program Officer

Laura Steckman

Q298. Please list any other Co-Program Officers (if applicable)

Q473. Submitting Official Email (if different than Principal Investigator)

Q462. By hitting the next button, you are confirming that you are submitting a [Final Performance Report](#). The rest of the survey will be conditional upon the answer to this question and you will not be able to change the responses on the previous page.

Q441.

Loading Publication Data

Q372. Our servers are contacting the Cross Reference API to see what information we already have for your award number. If your award number was not flagged on the Cross Reference website, you may have to manually enter additional publication information (this page will automatically proceed if nothing loads after 30 seconds).

We have found your results in the publication database

First Click: 0
Last Click: 0
Page Submit: 9.4
Click Count: 0

Q442.

Publications found in Database

This question was not displayed to the respondent.

Q376. Selecting Relevant Publications

These publications were retrieved from the Cross Reference open source publication database. This set of publications may or may not be a comprehensive list of your publications. You will be asked in a later question if you have additional publications to report on.

This question was not displayed to the respondent.

Q444.

Reported Publications

Q381. **Publications:** *Publication 1*

Please write your DOI number for any additional publications you have to report. If your publication does not have a DOI number associated, please leave this section blank and proceed to the next section where you can manually input your publication information.

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Example: <https://doi.org/10.1007/s10994-017-5633-9>

Q385.
Publication 1

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Q411. Publication Type

- ☐ Journal Article (Published)
- ☐ Journal Article (Pre-Print)
- ☐ Conference Proceeding
- ☐ Book
- ☐ Book Chapter
- ☐ Monograph
- ☐ Thesis/Dissertation

Q431. Did you acknowledge AFOSR funding for this publication?

- ☐ Yes
- ☐ No

Q383.

Publication 1

Do you have another publication to report

- ☐ Yes
- ☒ No

Q379. Thank you for reporting your publications, you are now leaving this section. If at any point you would like to edit your responses, please use the Main Menu button and navigate to the appropriate section that you would like to edit.

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All DOI numbers begin with a 10 and contain a prefix and a suffix separated by a slash. The prefix is a unique number of four or more digits assigned to organizations; the suffix is assigned by the publisher and was designed to be flexible with publisher identification standards DO NOT include any spaces or other special characters that tend to break a url search (EX: %, &, or =).

Example: <https://doi.org/10.1007/s10994-017-5633-9>

This question was not displayed to the respondent.

Q385.

Publication

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Q431. Did you acknowledge AFOSR funding for this publication?

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Q383.

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Q379. Thank you for reporting your publications, you are now leaving this section. If at any point you would like to edit your responses, please use the Main Menu button and navigate to the appropriate section that you would like to edit.

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Q444.

Reported Publications

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Q443.

Participant, Partners and Collaborators Overview

Q409.

Participants:

You will be asked to provide the following information for: (1) PIs; and (2) each person who worked, and was funded by the project, during this reporting period. Provide the name and identify the role the person played in this project. Indicate the total number of months (including partial months) (Calendar, Academic, Summer) that the individual worked on this project. Using the project roles identified below, select the most senior role in which the person worked on the project for any significant length of time. For example, if an undergraduate student graduated, entered graduate school, and continued to work on the project, show that person as a graduate student, preferably explaining the change in involvement.

Partner and Collaborating Organizations:

You will be asked to describe partner organizations or collaborators who worked on this grant.

Partnering organizations or collaborators can include: academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the project, exchanged personnel, or otherwise contributed. If you do not have any additional partners to report, please leave this section blank.

Q449.

Grant Participants

Q399. Participant Name (Last, First)

Participant: 1

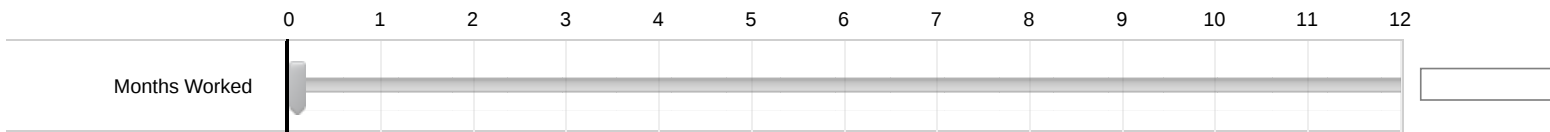
Hirshfield, Leanne

Q463. ORCID (Open Researcher and Contributor ID):

This is a unique, persistent identifier that is used to help researchers connect to their contributions. example: 0000-0001-5000-0007

Q400. Months Worked

Indicate the total number of months (including partial months) (Calendar, Academic, Summer) that the individual worked on this project.



Q401. Project Role

Co-Investigator

Q402. Briefly describe how this person contributed to the project.

Project management, experimental design, data analysis, personnel management

Q403. State, US territory, and/or country of residence

Colorado

Q404. International Business during Reporting Period.

Please check the boxes below if the situation applies to the person. Leave the boxes unchecked if these situations do not apply.

- ☐ 1) Did the individual collaborate with individuals located in a foreign country?
- ☐ 2) Did this individual travel to a foreign country as part of the collaboration?

Q405. Countries of International Collaboration

Please list the Country and the duration of stay in days
Ex: France, 12 days; Germany, 2 days

This question was not displayed to the respondent.

Q406. Do you have any additional participants that you would like to report on?

- ☒ Yes
- ☐ No

Q416. Thank you for reporting your participants, you are now leaving this section. If at any point you would like to edit your responses, please use the Main Menu button and navigate to the appropriate section that you would like to edit.

Q449.

Grant Participants

Q399. Participant Name (Last, First)

Participant: 2

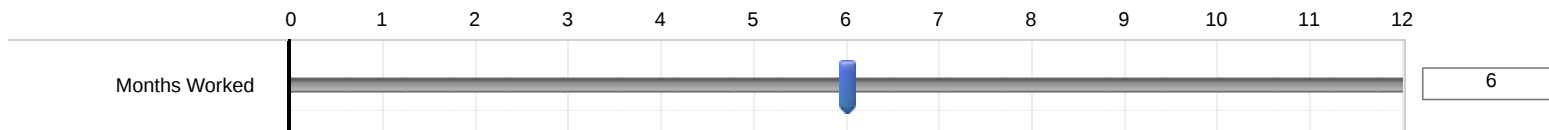
Kainerstorfer, Jana

Q463. ORCID (Open Researcher and Contributor ID):

*This is a unique, persistent identifier that is used to help researchers connect to their contributions.
example: 0000-0001-5000-0007*

Q400. Months Worked

Indicate the total number of months (including partial months) (Calendar, Academic, Summer) that the individual worked on this project.



Q401. Project Role

Co-Investigator

Q402. Briefly describe how this person contributed to the project.

Dr. Kainerstorfer focused on developing and testing the motion detection algorithms.

Q403. State, US territory, and/or country of residence

PA

Q404. International Business during Reporting Period.

Please check the boxes below if the situation applies to the person. Leave the boxes unchecked if these situations do not apply.

- ☐ 1) Did the individual collaborate with individuals located in a foreign country?
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☐ Yes

☒ No

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This question was not displayed to the respondent.

Q402. Briefly describe how this person contributed to the project.

This question was not displayed to the respondent.

Q403. State, US territory, and/or country of residence

This question was not displayed to the respondent.

Q404. International Business during Reporting Period.

Please check the boxes below if the situation applies to the person. Leave the boxes unchecked if these situations do not apply.

This question was not displayed to the respondent.

Q405. Countries of International Collaboration

Please list the Country and the duration of stay in days

Ex: France, 12 days; Germany, 2 days

This question was not displayed to the respondent.

Q406. Do you have any additional participants that you would like to report on?

This question was not displayed to the respondent.

Q416. Thank you for reporting your participants, you are now leaving this section. If at any point you would like to edit your responses, please use the Main Menu button and navigate to the appropriate section that you would like to edit.

This question was not displayed to the respondent.

Q449.

Grant Participants

This question was not displayed to the respondent.

Q399. Participant Name (Last, First)

Participant:

This question was not displayed to the respondent.

Q463. ORCID (Open Researcher and Contributor ID):

*This is a unique, persistent identifier that is used to help researchers connect to their contributions.
example: 0000-0001-5000-0007*

This question was not displayed to the respondent.

Q400. Months Worked

Indicate the total number of months (including partial months) (Calendar, Academic, Summer) that the individual worked on this project.

This question was not displayed to the respondent.

Q401. Project Role

This question was not displayed to the respondent.

Q402. Briefly describe how this person contributed to the project.

This question was not displayed to the respondent.

Q403. State, US territory, and/or country of residence

This question was not displayed to the respondent.

Q404. International Business during Reporting Period.

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Q406. Do you have any additional participants that you would like to report on?

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Q446.

Other Partners or Collaborators

Q417. Partner Organization: 1

Describe partner organization or collaborator who worked on this grant – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the project, exchanged personnel, or otherwise contributed.

If you do not have any additional partners to report, please leave this section blank.

Q418. Organization

University of Colorado Boulder

Q428. Contribution to Project

Experimental design, data collection, data analysis, project management

Q419. City

Boulder

Q421. State

CO

Q422. Country

USA

Q423. Please check the box if any of the below situations apply to this partner.

☐ Did this partner provide financial support?

☐ Did this partner provide in-kind support?

Q427. Do you have any more partners to report?

☐ Yes

☒ No

Q424. Thank you for reporting additional partners, you are now leaving this section. If at any point you would like to edit your responses, please use the Main Menu button and navigate to the appropriate section that you would like to edit.

Q446.

Other Partners or Collaborators

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This question was not displayed to the respondent.

Q418. Organization

This question was not displayed to the respondent.

Q428. Contribution to Project

This question was not displayed to the respondent.

Q419. City

This question was not displayed to the respondent.

Q421. State

This question was not displayed to the respondent.

Q422. Country

This question was not displayed to the respondent.

Q423. Please check the box if any of the below situations apply to this partner.

This question was not displayed to the respondent.

Q427. Do you have any more partners to report?

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Q445.

Intellectual Property Overview

Q331.

Inventions, patent applications, and/or licenses

Identify inventions, patent applications with date, and/or licenses that have resulted from the research. Submission of this information as part of an interim or final research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award.

Q72. Please Check Boxes if you have any intellectual property to report during this period

- ☐ Patents
- ☐ Inventions
- ☐ Licenses
- ☐ Technologies or Techniques
- ☐ Other Products (databases, software, models...etc)
- ☒ Nothing to report

Q447.

Patents

This question was not displayed to the respondent.

Q77. Patent Title

This question was not displayed to the respondent.

Q78. Patent Abstract

This question was not displayed to the respondent.

Q79. Patent Number

This question was not displayed to the respondent.

Q80. Country (the country which the patent resides)

This question was not displayed to the respondent.

Q82. Application Status

This question was not displayed to the respondent.

Q83. Date Issued (mm/dd/yyyy)

This question was not displayed to the respondent.

Q412. Do you have any additional patents that you would like to report on?

This question was not displayed to the respondent.

Q430. Thank you for reporting patents, you are now leaving this section. If at any point you would like to edit your responses, please use the Main Menu button and navigate to the appropriate section that you would like to edit.

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Q448.

Inventions

This question was not displayed to the respondent.

Q84. Invention Title

This question was not displayed to the respondent.

Q85. Invention Description

This question was not displayed to the respondent.

Q86. Inventors

This question was not displayed to the respondent.

Q432. Do you have any additional inventions that you would like to report on?

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Q85. Invention Description

This question was not displayed to the respondent.

Q86. Inventors

This question was not displayed to the respondent.

Q432. Do you have any additional inventions that you would like to report on?

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Q433. Thank you for reporting inventions, you are now leaving this section. If at any point you would like to edit your responses, please use the Main Menu button and navigate to the appropriate section that you would like to edit.

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Q448.

Inventions

This question was not displayed to the respondent.

Q84. Invention Title

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Q85. Invention Description

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Q87. License Title

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Q88. Application Date (mm/dd/yyyy)

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Q90. Date Issued (mm/dd/yyyy)

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Q453.

Technologies or Techniques

This question was not displayed to the respondent.

Q92. Description of Technology:

This question was not displayed to the respondent.

Q436. Do you have any additional technologies/techniques that you would like to report on?

This question was not displayed to the respondent.

Q437. Thank you for reporting technologies and techniques, you are now leaving this section. If at any point you would like to edit your responses, please use the Main Menu button and navigate to the appropriate section that you would like to edit.

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This question was not displayed to the respondent.

Q452.

Other Products

This question was not displayed to the respondent.

Q93. Select any other products during reporting period and write the number of products below

This question was not displayed to the respondent.

Q94. Describe any of the products listed above

This question was not displayed to the respondent.

Q451.

Section 2: Technical Report Submission

Q366. **Abstract:** Please insert your project abstract below:

Recent advancements in biotechnology have resulted in brain measurement devices that can non-invasively measure the functioning brain in people's natural environments. Functional Near-Infrared Spectroscopy (fNIRS) is such a technique, which measures the hemoglobin signatures related to neural activation. With the potential to monitor people's mental states non-invasively and in real-time, researchers have used fNIRS devices to measure a myriad of cognitive and emotional states in operational settings. Leading biotechnologists have created wireless implementations of fNIRS for real-time brain monitoring under normal working conditions. The device works by pulsing near-infrared light into the head, and using powerful light detectors to measure the light that is reflected back out of the head. The fNIRS is unique in its potential to take these measurements from a distance, without requiring contact with the head. While fNIRS implementations for measuring brain function have used source and detection fibers which are placed on the head of subjects directly, we have demonstrated that it is possible to modify this technology so that measurement of brain function can be done at a distance from the user. Specifically, we have developed a remote-fNIRS system (placed 0.6 meters from participants) to demonstrate the feasibility of taking fNIRS measurements from a distance and we have run a series of experiments to validate the device. While the results from our validation studies are encouraging, the remote-fNIRS has a significant limitation—it does not work when participants move. The current prototype system requires participants to have their heads in chin rests to avoid movement, and even with heads in chin rests we still note corruption to the signal caused by small motion artifacts. In this project we have been conducting research to enable the remote-fNIRS to take accurate measurements during times of participant movement. Enabling the remote fNIRS device to handle participant movement can ideally help us to achieve our long term goal: To develop the remote-fNIRS to a point that it can be further researched and validated by us and other researchers for a range of experiments under naturalistic laboratory conditions. In order to address motion with the remote-fNIRS, three areas need to be considered. First, the location of the subject's head needs to be known (motion tracking). Second, the effects of motion must be corrected, third we must evaluate the remote fNIRS system to ensure that we are indeed collecting reliable measurements of hemoglobin changes in the brain, rather than any other superficial data (from skin, scalp, superficial layers before reaching the cortex, etc.).

Q439. **Distribution Statement**

-Please verify that the report you are about to upload is cleared for public release (Distro A).

-In order to upload a PDF, your report must be publicly releasable.

-Please click the YES radio button below to confirm that your report is publicly releasable, then you will be able to upload a PDF copy of your report.

-If your report is not cleared for public release or is cleared for Distro B or higher release please directly email your report to technicalreports@us.af.mil

-You are allowed to upload one report document. If you need to change the file upload, re-click the submission box and select your correct file upload.

☒ Yes- Approved for Public Release (Distro A)

☐ No - Not Approved for Public Release (Distro B or higher, please send report to technicalreports@us.af.mil)

Q131. Technical Specifications/References Document Upload (This is your technical document that will be used to document the accomplishments and other relevant details not captured in this survey during your reporting period)

Please view the following report template to ensure all technical questions are answered in your report.

[AFOSR Report Template](#)

- The maximum file size for the Report Document is 100MB.
- Must be a pdf document

[Remote_fNIRS_Y3_report\[18879\].pdf](#)

466.5KB

application/pdf

Q460.

End of Survey

Q461. You have indicated that your Report is not approved for public release. Please submit your technical report directly to technicalreports@us.af.mil. Please also Cc your program officer. IF YOU DO NOT SUBMIT THIS REPORT TO THE APPROPRIATE EMAIL, YOUR ACCOUNT WILL BECOME DELINQUENT.

This question was not displayed to the respondent.

Q398. You are about to complete the AFOSR Deliverable Report. Please proceed forward if you would like to make your final submission. Otherwise, use the back button and the main menu button to review your response. YOU WILL NOT BE ABLE TO HIT THE BACK BUTTON TO EDIT THE SURVEY after this page.

Q450.

Submitting Official

This question was not displayed to the respondent.

Q12. Is this survey being submitted by someone other than the Principal Investigator?

This question was not displayed to the respondent.

Q13. Submitting Official

This question was not displayed to the respondent.

Q455.

Equipment Report Questions

This question was not displayed to the respondent.

Q120. What DoD relevant projects does this equipment enhance?

This question was not displayed to the respondent.

Q121. Status of Equipment: At this point in time please select one of the options below for the status of your equipment.

Embedded Data

EndLoop: 1

EndLoop_Participants: 1

EndLoop_Patents: 1

EndLoop_Partners: 1

EndLoop_Inventions: 1

EndLoop_Licenses: 1

EndLoop_Technologies: 1

Location Data

Location: ([42.9908](#), [-75.962](#))

Source: GeolIP Estimation



From: [Air Force Office of Scientific Research](#)
To: [Technical Reports](#)
Subject: [URL Verdict: Neutral][Non-DoD Source] Deliverable Received: FA9550-18-1-0074
Date: Friday, April 15, 2022 10:59:25 AM



OMA Team,
A new Final Performance has been submitted for your attention. Award
Number: FA9550-18-1-0074

Supporting
Report: https://afosr.gov1.qualtrics.com/WRQualtricsSurveyEngine/File.php?F=F_3M5c7k8HGfIbY0C

- Date Stamp: 10:56:47 , 4/15/2022
- Title: Development of a Remote-fNIRS Device for use Under Naturalistic Working Conditions
- DISTRIBUTION: Yes- Approved for Public Release (Distro A)
- Principal Investigator: Mark R. Costa
 - PI Email: mrcosta@syr.edu
- Program Officer: Laura Steckman
- Report Type: Final Performance
- Reporting Period
 - Start Date: 01/16/2018
 - End Date: 01/15/2022
- Award Number: FA9550-18-1-0074
- Report Due Date: 04/15/2022

ABSTRACT:

Recent advancements in biotechnology have resulted in brain measurement devices that can non-invasively measure the functioning brain in people's natural environments. Functional Near-Infrared Spectroscopy (fNIRS) is such a technique, which measures the hemoglobin signatures related to neural activation. With the potential to monitor people's mental states non-invasively and in real-time, researchers have used fNIRS devices to measure a myriad of cognitive and emotional states in operational settings. Leading biotechnologists have created wireless implementations of fNIRS for real-time brain monitoring under normal working conditions. The device works by pulsing near-infrared light into the head, and using powerful light detectors to measure the light that is reflected back out of the head. The fNIRS is unique in its potential to take these measurements from a distance, without requiring contact with the head. While fNIRS implementations for measuring brain function have used source and detection fibers which are placed on the head of subjects directly, we have demonstrated that it is possible to modify this technology so that measurement of brain function can be done at a distance from the user. Specifically, we have developed a remote-fNIRS system (placed 0.6 meters from participants) to demonstrate the feasibility of taking fNIRS measurements from a distance and we have run a series of experiments to validate the device. While the results from

our validation studies are encouraging, the remote-fNIRS has a significant limitation—it does not work when participants move. The current prototype system requires participants to have their heads in chin rests to avoid movement, and even with heads in chin rests we still note corruption to the signal caused by small motion artifacts. In this project we have been conducting research to enable the remote-fNIRS to take accurate measurements during times of participant movement. Enabling the remote fNIRS device to handle participant movement can ideally help us to achieve our long term goal: To develop the remote-fNIRS to a point that it can be further researched and validated by us and other researchers for a range of experiments under naturalistic laboratory conditions. In order to address motion with the remote-fNIRS, three areas need to be considered. First, the location of the subject's head needs to be known (motion tracking). Second, the effects of motion must be corrected, third we must evaluate the remote fNIRS system to ensure that we are indeed collecting reliable measurements of hemoglobin changes in the brain, rather than any other superficial data (from skin, scalp, superficial layers before reaching the cortex, etc.).

Y3 Report
Development of a Remote-fNIRS Device for use Under Naturalistic Working Conditions
FA9550-18-1-0074

PI: Mark Costa, Assistant Research Professor, Syracuse University

Co-PI: Leanne Hirshfield, Associate Research Professor. Institute of Cognitive Science, University of Colorado, Boulder.

Co-PI: Jana Kainerstorfer, Assistant Professor of Biomedical Engineering, Carnegie Mellon University.

1 Problem Space

Recent advancements in biotechnology have resulted in brain measurement devices that can non-invasively measure the functioning brain in people's natural environments. Functional Near-Infrared Spectroscopy (fNIRS) is such a technique, which measures the hemoglobin signatures related to neural activation. With the potential to monitor people's mental states non-invasively and in real-time, researchers have used fNIRS devices to measure a myriad of cognitive and emotional states in operational settings [1-5]. Leading biotechnologists have created wireless implementations (Fig 1) of fNIRS for real-time brain monitoring under normal working conditions [6]. The device works by pulsing near-infrared light into the head, and using powerful light detectors to measure the light that is reflected back out of the head. The fNIRS is unique in its potential to take these measurements **from a distance**, without requiring contact with the head. While fNIRS implementations for measuring brain function have used source and detection fibers which are placed on the head of subjects directly, we have demonstrated that it is possible to modify this technology so that measurement of brain function can be done at a distance from the user.

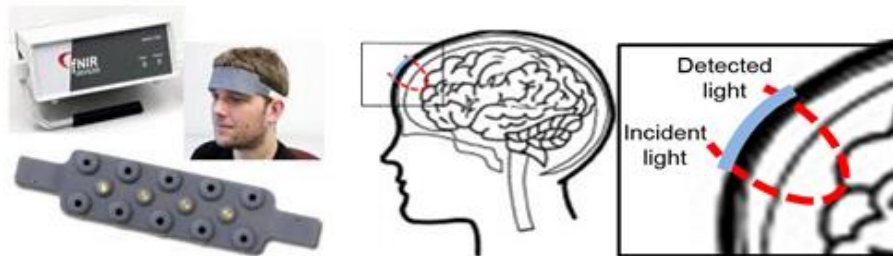


Figure 1: Left: an example of wireless fNIRS currently available from Biopac. Right: Near-infrared light is pulsed into the brain cortex. Reflected light is determined with optical detectors.

Specifically, we have developed a remote-fNIRS system (placed 0.6 meters from participants) to demonstrate the feasibility of taking fNIRS measurements from a distance and we have run a series of experiments to validate the device. While the results from our validation studies are encouraging, the remote-fNIRS has a significant limitation—it does not work when participants move. The current prototype system requires participants to have their heads in chin rests to avoid movement, and even with heads in chin rests we still note corruption to the signal caused by small motion artifacts. In this project we have been conducting research to enable the remote-fNIRS to take accurate measurements during times of participant movement. Enabling the remote fNIRS device to handle participant movement can ideally help us to achieve our long term goal:

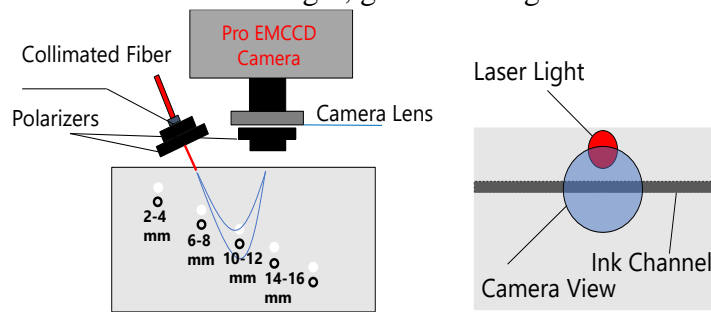
To develop the remote-fNIRS to a point that it can be further researched and validated by us and other researchers for a range of experiments under naturalistic laboratory conditions.

In order to address motion with the remote-fNIRS, three areas need to be considered. First, the location of the subject's head needs to be known (motion tracking). Second, the effects of motion must be corrected, third we must evaluate the remote fNIRS system to ensure that we are indeed collecting reliable measurements of hemoglobin changes in the brain, rather than any other superficial data (from skin, scalp, superficial layers before reaching the cortex, etc.).

2 Y2 Progress

2.1 Detection of inclusion in phantoms – depth sensitivity

In order to evaluate how deep a non-contact imaging system can see inside tissue, phantoms made from silicone and titanium oxide were used to mimic brain tissue. Optical properties were matched to mimic brain tissue. The phantoms were fabricated to have hollow channels of varying depths ranging from 2-20 mm that served as pathways for India ink to pass through. Ink was used as absorption contrast to mimic hemodynamic changes in the brain. A 785 nm NIR laser module [MCLS1, Thorlabs] was used as the source to emit the NIR light, guided through a multimode fiber [M42L02, Thorlabs]. The laser illuminated a spot on the surface of the phantom, adjacent to the hollow channel, as seen in Figure 2. The ProEM HS: 512BX3 EMCCD camera [Princeton Instruments] was used to take 512 by 512 pixel images of the reflected photons. Each pixel in the camera functioned as detector, with varying source-detector distances based on distance to the source. The source light was collimated [F220FC-780, Thorlabs]. The collimated source and detector were cross polarized using two linear polarizers [LPNIR100-MP2, Thorlabs] in order to eliminate surface reflections. The source and detector were kept a constant 38 mm above the phantom.



showing channel depths and projected photon path. (Right) Top view demonstrating camera view in blue with laser beam spread in red, which saturates the camera at these locations.

Trials were done at each varying channel depth with multiple images collected per trial. The images were separated into two groups, no ink flow, and ink flow. Multiple images per trial were taken and averaged to reduce noise and create an average image of no ink flow or ink flow. The average image of ink flow was subtracted from the average image of no ink flow which resulted in an image displaying changes in light intensity due to absorption of the ink.

Detectability of the channel as a function of depth was evaluated. Light absorption changes were detected at depths of 2-16 mm as shown in Figure 3. Reliable absorption changes were detected up to 12 mm, which demonstrates that the human brain cortex should be possible to be reached with this imaging system.

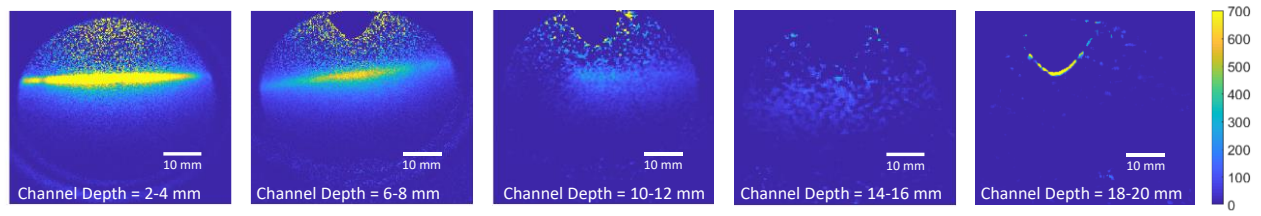


Figure 3: Yellow areas represent sections where large amounts of light were absorbed, which corresponds to the absorption inclusion. Absorption changes were reliably detected up to 12 mm, which is in the order of cerebral depth from the skin surface.

Our data suggests that non-contact fNIRS can potentially detect absorption changes in the brain. Therefore, we have shown that non-contact fNIRS should be possible.

Validation with Monte Carlo simulations

We used a mesh-based Monte Carlo solver for simulating photon propagation (<http://mcx.space/wiki/index.cgi?MMC>). The experimental setup described above was simulated.

Specifically, we modeled different channel depths of 2.5, 7.5, 12.5, 17.5 mm with a channel radius of 1.5 mm. Background optical properties were set to $\mu_a = 0.011 \text{ mm}^{-1}$ and $\mu_s' = 1.41 \text{ mm}^{-1}$. Each pixel in the mesh was $1 \times 1 \text{ mm}$, the phantom size was $30 \text{ mm} \times 60 \text{ mm} \times 30 \text{ mm}$, and the field of view was $58 \times 58 \text{ mm}$. Two simulations were run per channel depth. One without absorption in the channel (same as background) and one with absorption changes, simulating hemodynamic changes in the brain. The source location in respect to the channel was changed, as seen in Figure 4. We varied the source location on the phantom surface in order to find the ideal location based on channel depth. Figure 4 shows some of the results for the 2.5 and 17.5 mm channel.

The reflected photons were measured in terms of flux and the difference between two images (with and without absorption contrast in the channel) were calculated. A cross section perpendicular to the channel is displayed in Figure 3. What is shown is that the shallow channel shows the largest contrast when the source is close and further channels do not carry much information about the inclusion. The deep channel is noisy overall, but shows that

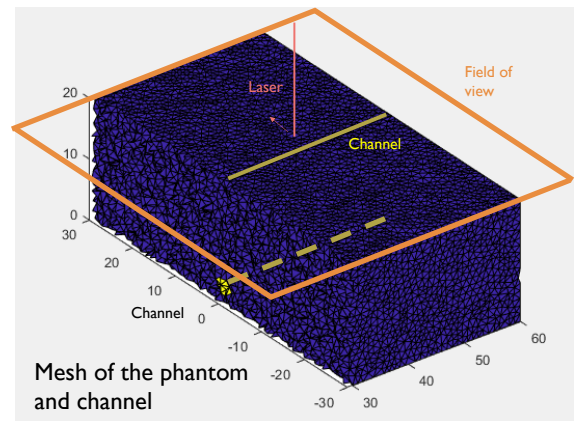


Figure 4: Layout of the Monte Carlo simulation. The channel depth and location of the source was varied in order to identify the best source-detector distance for a given inclusion depth. **Figure 2:** (Left) Side view

the relative sensitivity to channel is great even when the source is further away.

Overall, our results, based on experimental validation and Monte Carlo simulations, show

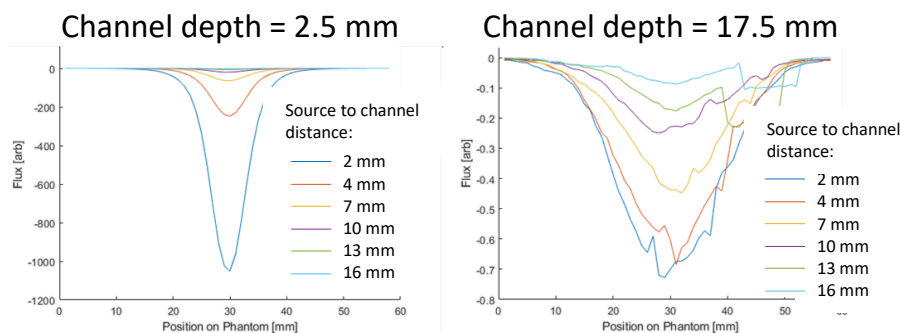


Figure 5: Results from Monte Carlo simulations. Left: Difference image cross-section for the shallow channel at different locations of the source in respect to the channel. Right: Same as left but for the deep channel.

that non-contact imaging of inclusion is possible even at depths capable of reaching cortical layers of the brain.

2.2 Motion tracking



Fig 6: A 3d mesh of a student's face using the Structure.io sensor.

Markerless motion tracking of the head/face is largely a solved problem, with high quality temporal and spatial resolution achieved by several face tracking systems. Therefore, our work on that front has involved looking for a motion tracking hardware/software combination that can track a point on the forehead accurately, and quickly, while also providing real-time access to movement data. We explored three motion tracking hardware/algorithm combinations. First, we implemented code in Python to use the You-Only-Look-Once (YOLO) face detection [7] algorithm, followed by optical flow for point tracking (for tracking the point light source of the remote fNIRS) within the face. The optical flow technique is based on prior work of one of the

graduate students working on this project [8]. The resulting YOLO architecture was fast, processing images in real-time at 45 frames per second [7], but it did not provide adequate spatial in pilot testing. Second, we explored a product from a company called Tracoline. Tracoline has developed markerless motion tracking hardware, which has been used for motion tracking in fMRI settings. We were motivated by articles based on Tracoline's markerless motion tracker that have been published. In one such article, the research team used Tracoline's motion tracking software to integrate markerless head motion tracking with prospectively corrected neuroanatomical MRI sequences and they investigated high-frequency motion correction during imaging echo trains [9]. After multiple discussions with the Tracoline team it was determined that Tracoline would need to do extensive R&D to configure their motion tracking hardware to work in naturalistic settings outside of the fMRI magnet. This was not a feasible approach due to time and cost constraints. Finally, we tested and then purchased a Structure.io Camera, and we implemented an Iterative Closest Point Algorithm to track one point in the 3d point cloud. Structure.io has performed incredibly well in our pilot tests—constructing a 3d mesh model a face (Fig 5). We then adapted the iterative closest point (ICP) algorithm to find the region of interest (a point from a light source on the forehead) in the re-constructed point cloud. This approach achieves our desired spatial and temporal performance, and it provides us with access to the real-time movement data, making the Structure.io/point cloud detection the best approach for motion tracking.

2.3 Prospective motion correction

With the optimum motion tracker via Structure.io and point detection algorithm implemented, Y2 also involved moving onto the harder problem of motion correction in the remote fNIRS. Advances in the fMRI domain have resulted in combined motion tracking with real-time correction, capable of quantifying rigid-body motion. This technique is often called "prospective motion correction." For a review of prospective motion correction in the fMRI field, see [10]. We are currently exploring two approaches for prospective motion correction: First, our hardware/software approach will involve using a laser beam steering approach whereby a microcontroller or actuator controls the movement of a mirror, which modifies the path of the light source being pulsed at the head. Beam steering is a huge field, with hardware solutions available for a range of applications. We are currently

reviewing the products available from several companies involved in the fast steering mirror industry. Second, we will explore a software-based motion correction technique that can be done on the back-end in real-time. The approach uses a convolutional neural network (CNN) classifier to take in corrupted remote-fNIRS data with information from the motion tracking system. The CNN will then output corrected fNIRS data, as done recently on corrupted fMRI data by Duffy et. al. (2018) and Pawar et. al (2018) [10-12]. These approaches could conceivably be combined to achieve an optimum solution-hardware tilting mirrors to steer and correct the physical beam combined with machine learning on the back-end to further correct the resulting fNIRS signal.

3 Y3 Progress

During the last year of the project we experienced a hardware malfunction, whereby our light source unit from Thorlabs stopped functioning properly, and it resulted in errors being thrown in LabView whenever running the remote fNIRS system. Unfortunately, after extensive troubleshooting, we were able to identify that the light source multiplex unit was no longer functioning properly, causing a variety of errors to be thrown while the remote fNIRS was acquiring data. With the underlying system not working properly, we re-focused our efforts in Y3 on i) publishing the results from the progress made during Y1 and Y2 in a Journal (submitted to International Journal of Human Computer Studies) and ii) working in the CMU lab to continue to validate the depth sensitivity of the remote fNIRS system using Monte Carlo simulations. The issue with the NIR laser module [MCLS1, Thorlabs] is reflected in the fact that we were underspent on the grant at the end of the project.

4 References

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